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ADVANCES IN COMPOSITES TECHNOLOGY

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16. Abstract

Major advancements have been made in the development of advanced composite materials during the past decade. Composites have moved from the research laboratory to the production floor, where they are baseline for many aerospace hardware components. Design data bases and in-service durability have been established for a variety of service environments. Many of the applications of composites have been for replacement of metal parts on existing designs with an average weight savings of approximately 20 to 25 percent. However, the full weight reduction potential of composites can only be realized when the damage tolerance of composites is increased such that they can be utilized at strain levels significantly higher than the 0.004 limit currently used in many aerospace applications.

A significant level of research is currently focused on the development of tough resins and high strain fibers in an effort to gain improved damage tolerance. Moderate success has been achieved with the development of new resins such as PEEK and additional improvements look promising with new thermoplastic resins. Development of innovative material forms such as 2-D and 3-D woven fabrics and braided structural subelements is also expected to improve damage tolerance and durability of composite hardware.

The new thrust in composites is to develop low-cost manufacturing and design concepts to lower the cost of composite hardware. Processes being examined include automated material placement, filament winding, pultrusion, and thermoforming. The factory of the future will likely incorporate extensive automation in all aspects of manufacturing composite components.

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INTRODUCTION

The desire for new materials to improve the performance and reduce the weight of aircraft has provided the impetus for a national emphasis on composite materials over the past several years. The development of high-strength glass and high-modulus boron fibers in 1960 (ref. 1) was the key technology development that focused attention on the potential of fiber-reinforced composites. In the mid-1960's, graphite fibers became commercially available and rapidly gained acceptance as the principal reinforcement fiber for high-performance composites because of their high specific strength and modulus. The development of Kevlar aramid fibers, manufactured by E. I. du Pont de Nemours & Co., Inc. (commercially available in 1971), was also a very significant technology development because these fibers have high tensile strength, high stiffness, low density, and a high degree of toughness (ref. 2). Glass, Kevlar, boron, and graphite fibers are commercially available with a broad range of strengths (300 to 700 ksi) and stiffnesses (10 to 70 Msi). Further improvements in fiber properties are expected with pitch-base graphite fibers expected to become available with an elastic modulus as high as 120 Msi. PAN-base graphite with strength in excess of 700 ksi is currently under development, and ultimately achieving a strength of 1 Msi appears possible.

The matrix materials most commonly used for high-performance composites include polyesters, epoxies, polyimides, thermoplastics, aluminum, magnesium, and carbon. A large number of other matrices have been investigated for a host of special applications to meet particular design requirements but do not represent large-volume usage of materials.

Because the aerospace industry is the primary user of advanced composite materials, the discussion in the remainder of this paper will be focused on aerospace applications. The examples to be discussed will also center around graphite-reinforced polymers because these materials are the primary materials being used today and are expected to be the most widely used structural materials for high-performance aerospace structures of the future. Four general areas of composites technology will be presented. First, a look at the market projections for the use of PAN-base graphite fibers will be discussed to indicate the potential growth of the market for composite materials. Second, the types of applications where composites are currently being used and are expected to be used during the next few years will be discussed. Materials limitations and current research to improve composites will be presented. Finally, concepts for low-cost automated fabrication and design will be presented to illustrate approaches to making composite structures more affordable.

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POTENTIAL WEIGHT SAVINGS TRENDS FOR FUTURE STRUCTURAL MATERIALS

The thrust to build lighter weight, more fuel efficient aircraft has provided the impetus for continued development of advanced materials. An estimate of the potential structural weight savings which can be realized by the application of advanced structural materials (ref. 3) is shown in figure 1. Advanced powder metallurgy alloys and aluminum/lithium alloys are expected to offer a 10- to 15-percent weight savings over conventional ingot metallurgy aluminum alloys. Advanced aluminum alloys are expected to reduce weight because of their improved yield strength and fracture toughness. Aluminum/lithium with 3 percent lithium has approximately a 10-percent lower density than conventional aluminum alloys. Also, the higher strength properties of these alloys can result in a lighter weight structure.

Advanced composites have the potential to give a 30- to 40-percent weight reduction. This reduction, however, depends on the development of higher strain-to-failure fibers and tough resins to improve the damage tolerance and impact resistance of current composites. To reach the 30- to 40-percent weight savings goal, composite structures must be capable of a design ultimate strain level of 0.006 instead of the current limit of 0.004. The limitation on strain level will be discussed in later figures and the material development efforts currently under way to increase this level will be highlighted.

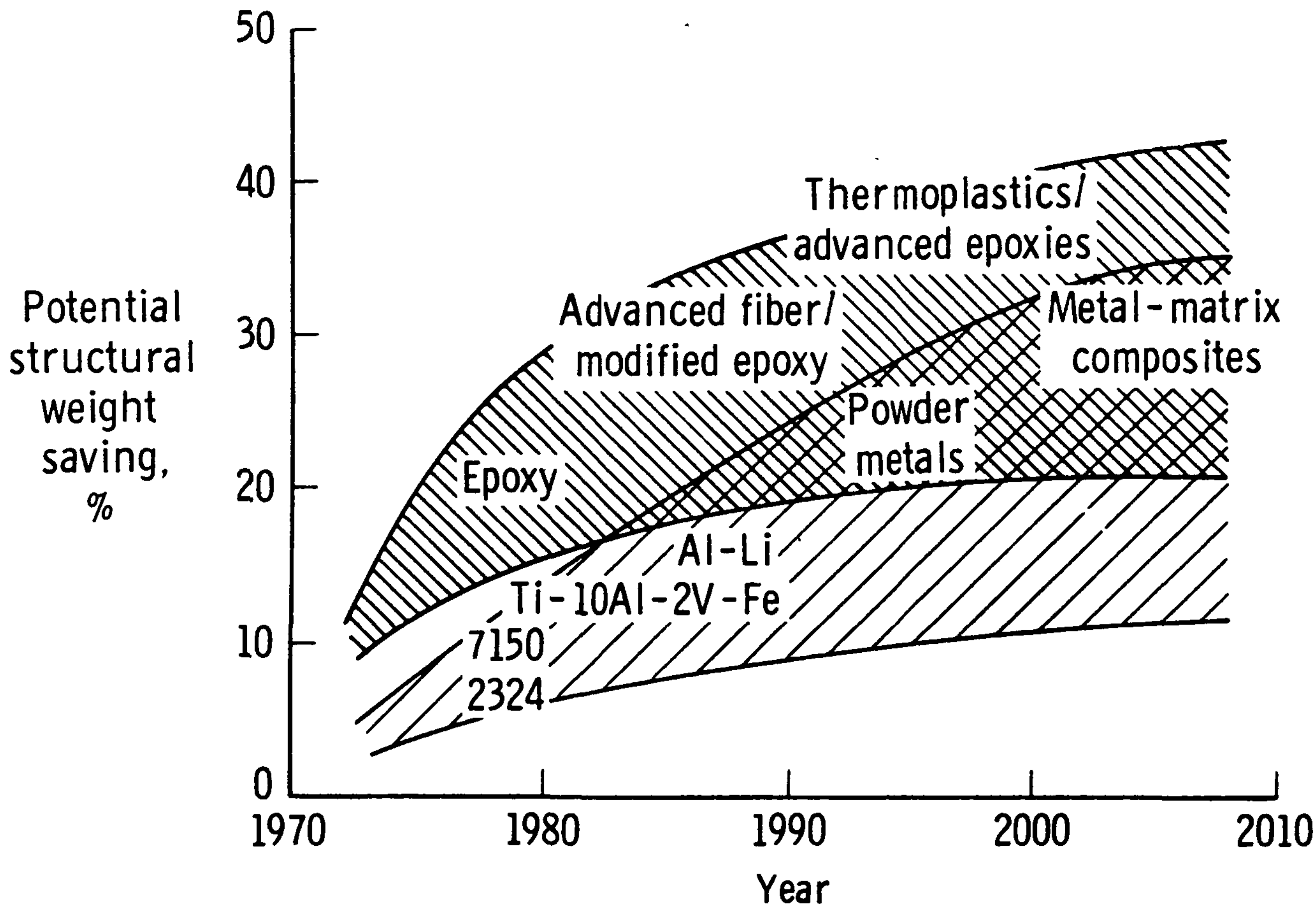

Figure 1

COST REDUCTION OF GRAPHITE FIBERS

The current technology for producing carbon fibers generally centers on the thermal decomposition of various organic precursors. Rayon, polyacrylonitrile (PAN), and pitch have been found to offer the greatest potential in terms of carbon yield and cost. During the mid-1960's, rayon and PAN-base graphite fibers became available in research quantities and sold for well over $100/pound. During that period of time, several patents (ref. 4) were awarded for carbon fibers based on PAN precursors. Fibers of very high tensile modulus of elasticity (70 Msi) and tensile strengths (300 ksi) were reportedly made by several researchers (ref. 4).

The improvement in fiber properties during the mid- to late-1960's resulted in graphite being selected for reinforcement of resin-matrix composites being developed for structural applications. Typical early applications were the wing leading edge of the Northrop F-5, the shoulder fuselage panels of the F-111, the main landing gear doors of several fighter aircraft, and secondary structures (flaps, spoilers, etc.) for commercial aircraft such as the B-737, the DC-10, and the L-1011 (ref. 5). The first production application of a graphite/epoxy structure was the F-111 underwing fairing in 1971. The F-15 speed brakes, F-16 vertical stabilizer skins, and the F-16 horizontal stabilizer are currently produced from graphite/epoxy. The expanding market for composites during the 1970's resulted in the cost of graphite fibers decreasing from over $100/pound to approximately $20/pound in then-year dollars (fig. 2). The cost of PAN-base fibers is not expected to change rapidly in the future, but the properties are expected to increase. PAN-base fibers with strengths as high as 1 Msi and modulus values in the range of 45 to 48 Msi are expected to be commercially available with costs approximately 30 percent higher than current PAN-base fibers (ref. 6).

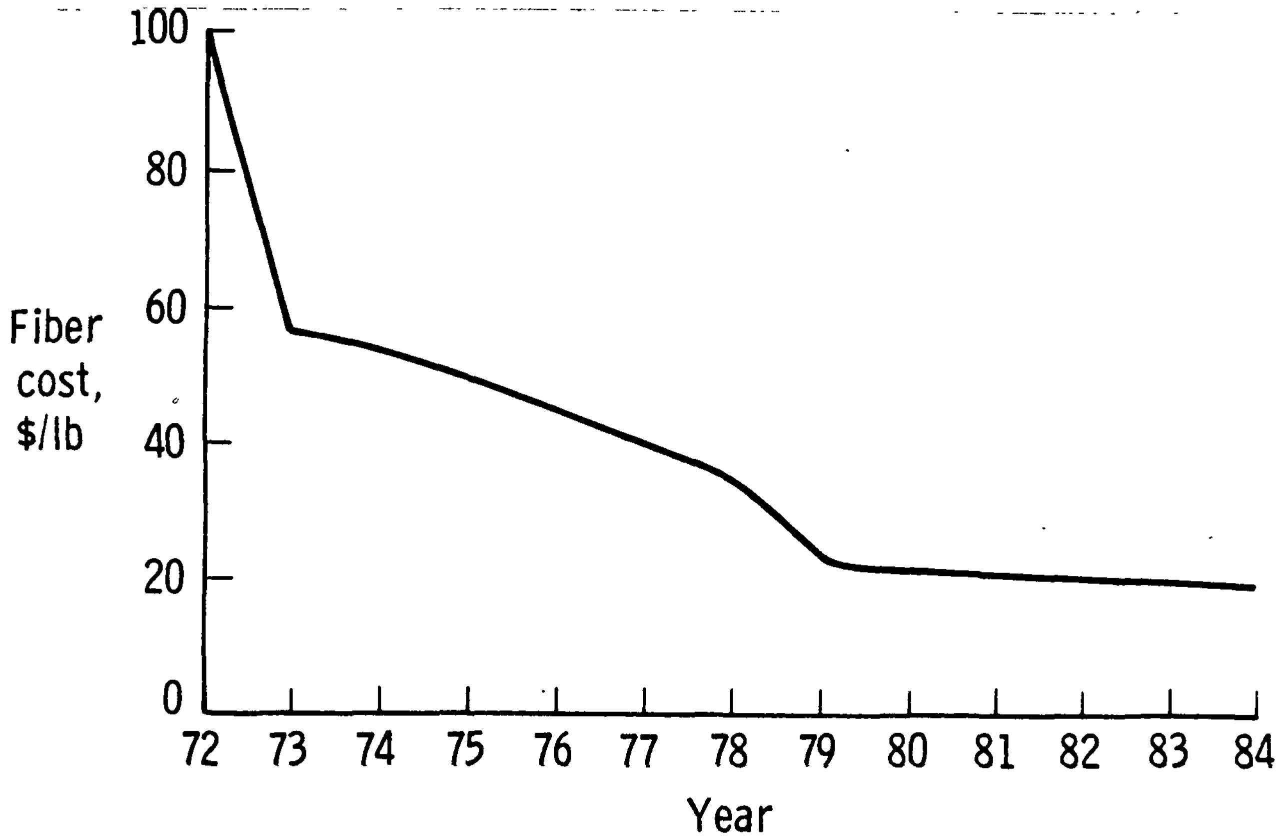

Figure 2

COST COMPARISON OF GRAPHITE FIBERS AND FABRICATED STRUCTURES

PAN-base graphite fibers with tensile modulus of elasticity of approximately 30 Msi are commercially available for about $20/pound (ref. 6). Higher modulus varieties sell for approximately $40/pound. The cost of the PAN precursor and the high processing temperature required to attain high strength and modulus are the key factors determining the cost of the fibers. Pitch fibers currently sell for $30/pound for the low modulus variety (20 to 25 Msi) and for over $1200/pound for 100 Msi fibers.

Graphite fibers are available in a variety of forms: continuous, woven fabrics, mat, or chopped. The most common forms of continuous graphite fibers sold today are tows, yarns, rovings, and tape. Tape is made by laying numerous (e.g., 300) tows or yarns side by side on a backing. Prepreg tape with the resin system infiltrated into the fibers generally sells for approximately $40/pound (fig. 3).

The final cost of finished aircraft structure can be in the range of $100 to $400/pound, depending on the complexity of the structure and the certification testing and inspection performed. For these types of expensive structures, material costs may be only a small part of total production costs and relatively expensive graphite fibers can be considered.

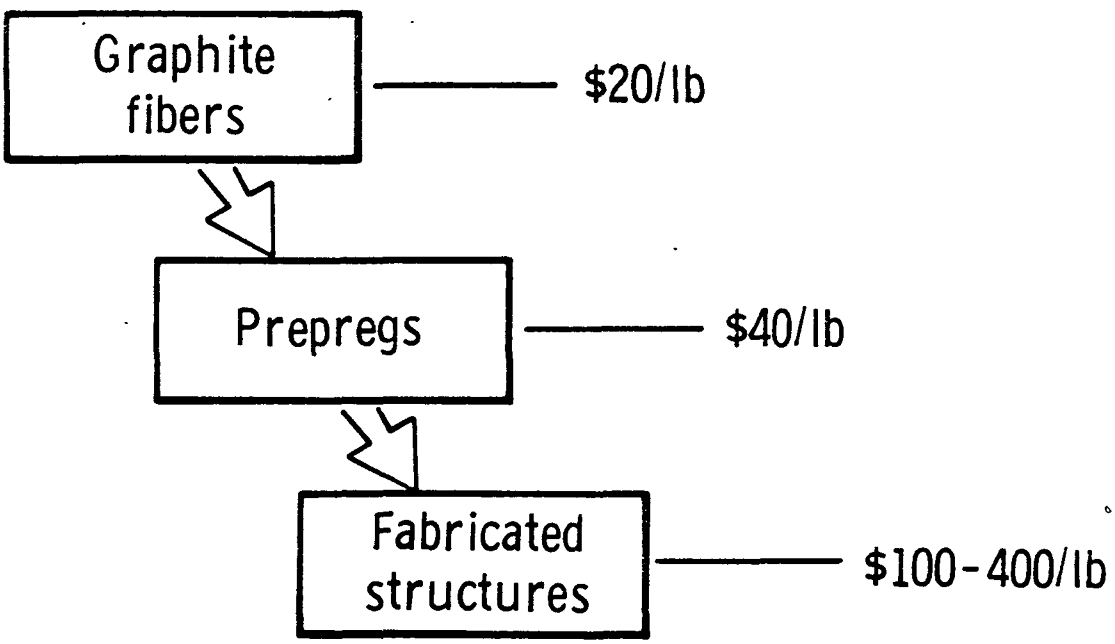

Figure 3

PROJECTED WORLD-WIDE USAGE OF PAN-BASED GRAPHITE FIBERS

The world market for PAN-based graphite fibers in 1984 is approximately 4-million pounds. The market is projected (ref. 6) to grow at a rate of 20 to 25 percent per year for the next 5 years (fig. 4). Slightly more than half of the market is in the United States, with the bulk (75 percent) of the U.S. market being aerospace. The market in Europe is also dominated by aerospace and the market in Japan is expected to grow rapidly in aerospace during the next several years. Most of the fibers used in Taiwan are used in sporting equipment.

The estimated world capacity for the production of PAN-based graphite fibers in 1984 is approximately 10- to 11-million pounds (ref. 6). The U.S. capacity is 3-million pounds, Europe's is about 2-million pounds, and Japan's is about 6-million pounds. The total capacity is therefore more than two-and-one-half times the world market and, with the additional capacity expected to come on line, the trend of excess world capacity is expected to continue.

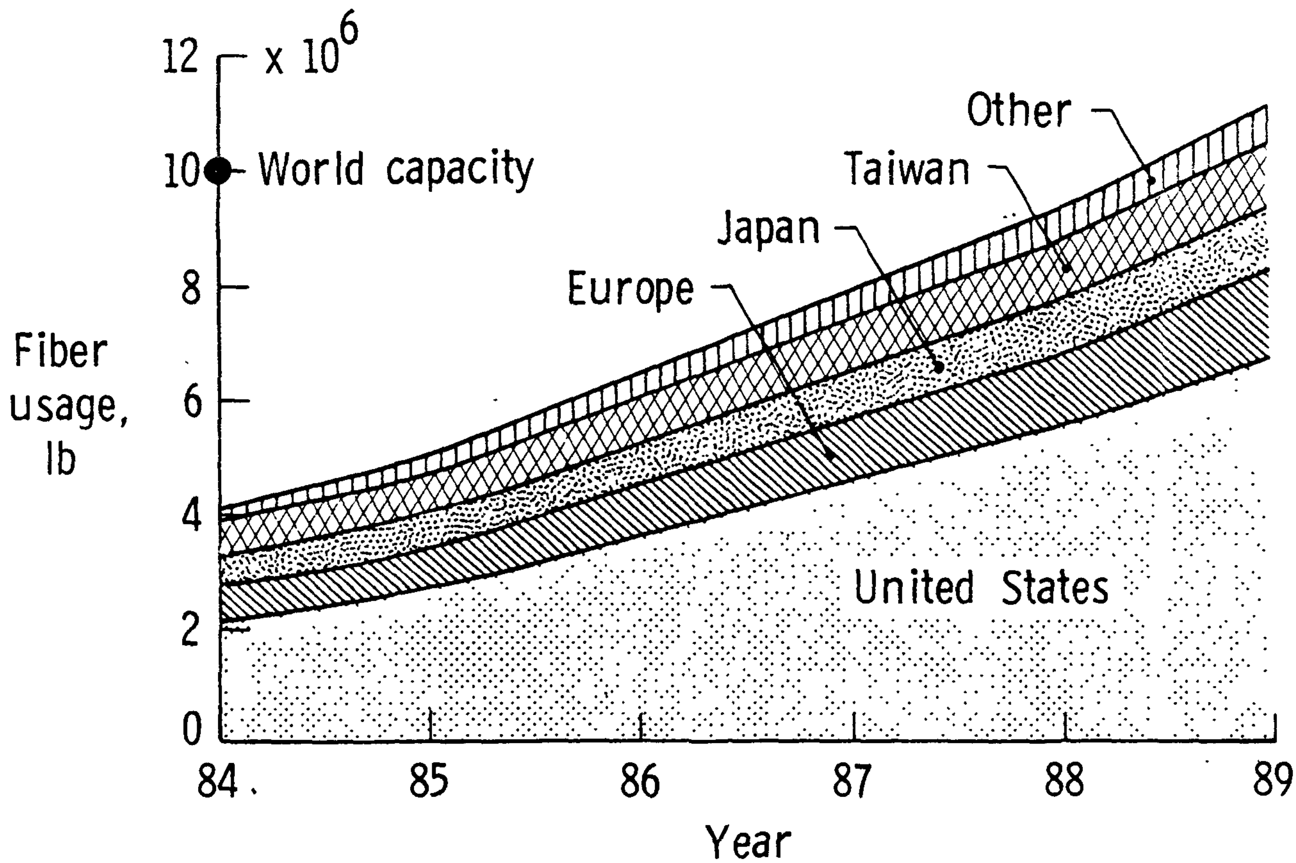

Figure 4

U.S. PAN-BASED GRAPHITE FIBER MARKET

The projected market for consumption of PAN-based graphite fibers (ref. 6) in the U.S. is shown in figure 5. The market is shown divided into four major categories: automotive, industrial, sports, and aerospace. The total market is expected to increase by more than 5 times during the next 8 years, with the major growth taking place in aerospace. The use of PAN-based fibers in the automotive and industrial markets is also expected to increase by two to three times during the same period. However, the use of composites in the nonaerospace market may show an even larger growth as alternate reinforcement fibers (that are lower cost than PAN-based graphite) are selected for applications where the high specific properties of graphite are not required.

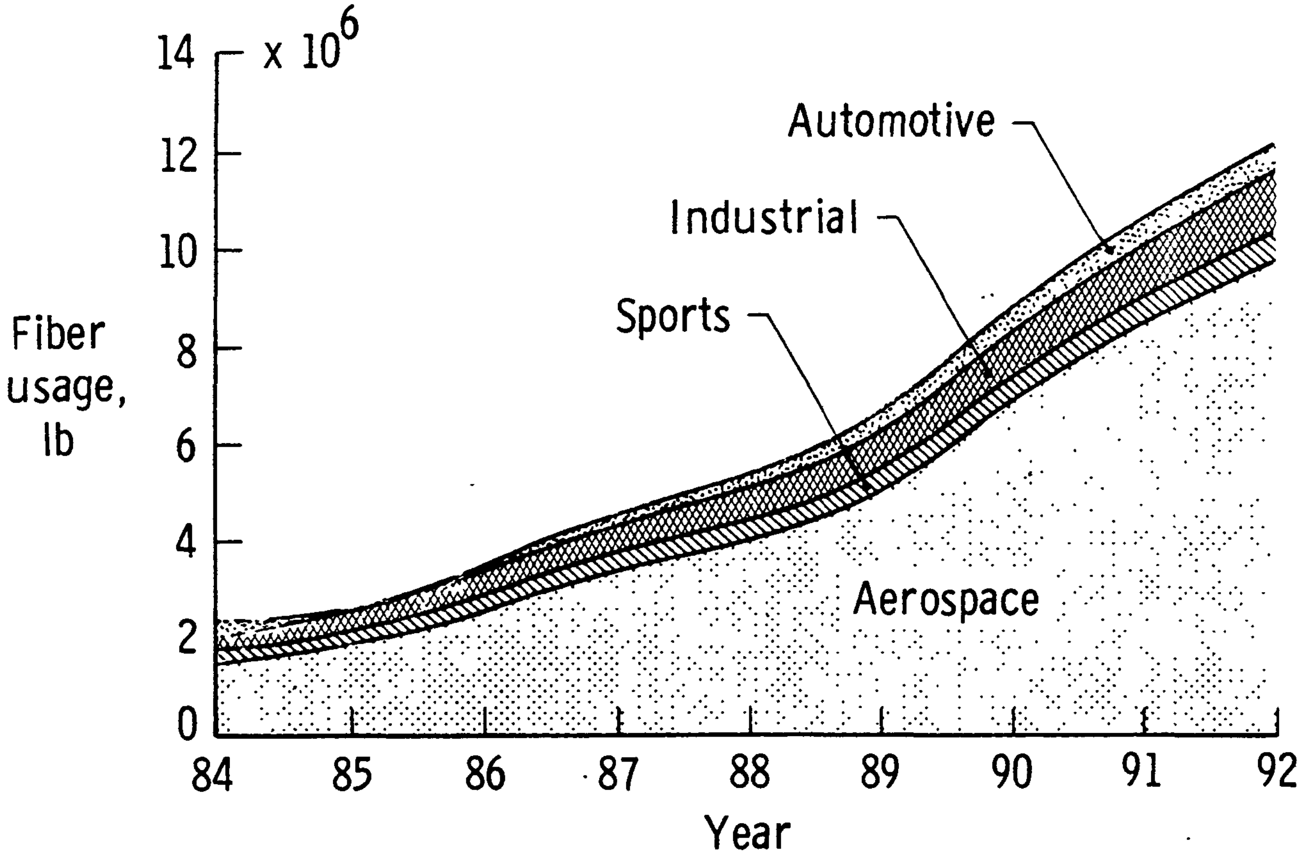

Figure 5

ADVANCED COMPOSITE STRUCTURAL APPLICATIONS ARE CONTINUALLY EXPANDING

During the past decade, the application of advanced composites to military fighter aircraft has made significant gains. Three aircraft, F-15, F-18, and AV-8B (fig. 6), that are produced by the McDonnell Aircraft Company have 2, 10, and 27 percent, respectively, composite structure by weight. The next generation aircraft, Advanced Tactical Fighter (ATF), could employ approximately 40 percent composite structure by weight. Details of the structural designs are presented in reference 7. The technology has progressed from secondary graphite and boron reinforced composite structures for the F-15 to mostly graphite/epoxy primary wing and fuselage structures for the AV-8B. More extensive applications are expected for the ATF; however, epoxies will not be the predominant matrix material because of higher temperature requirements. It is expected that polyimides, bismaleimides, or metal-matrix materials will be required to meet the 400°F design requirements for the ATF aircraft. As more composites enter into production, it is essential that low-cost automated fabrication concepts be developed. Concepts that may be included in the factory of the future are discussed in reference 8.

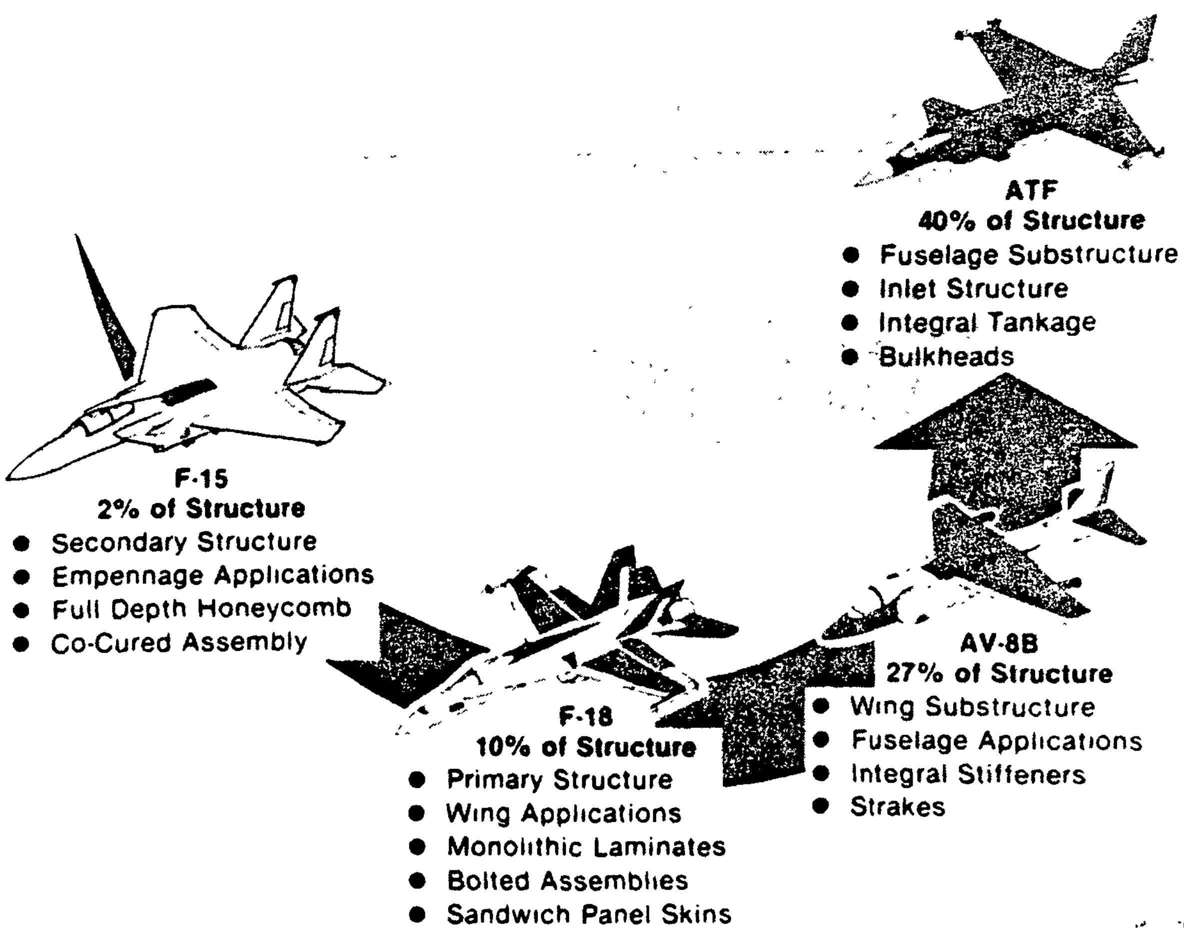

Figure 6

COMPOSITE USAGE TREND ON BOEING COMMERCIAL TRANSPORTS

The first new fiber-reinforced composite material used on Boeing aircraft was fiberglass/epoxy (ref. 9). Boeing has developed an extensive service data base on secondary fiberglass/epoxy composite components on 707, 727, 737, and 747 aircraft (fig. 7). Although the 747 aircraft has almost 30 percent of the surface area covered with fiberglass/epoxy, only 1 percent of the structural weight is involved. By the early 1970's, graphite/epoxy and Kevlar/epoxy materials had matured to the point where structural development and service evaluation programs were initiated. The purpose of these programs was to establish confidence in the long-term service durability of the newer materials. The success of these and other composite development programs, together with significant price reductions for graphite fibers, led Boeing to make production commitments to advanced composite secondary structures for the 757 and 767 transport aircraft. Because of the increased structural efficiency of graphite and Kevlar reinforced composite components, standard fiberglass and aluminum secondary structures were replaced during the early design phases of the 757 and 767 aircraft. Three percent by weight of the structure was fabricated with Kevlar and graphite compared to only one percent structural weight of fiberglass/epoxy in the 747 aircraft. Because of improved damage tolerance, graphite/Kevlar hybrids were used in high impact-prone areas of the aircraft. Details of the composite applications on the 767 aircraft are shown in figure 8.

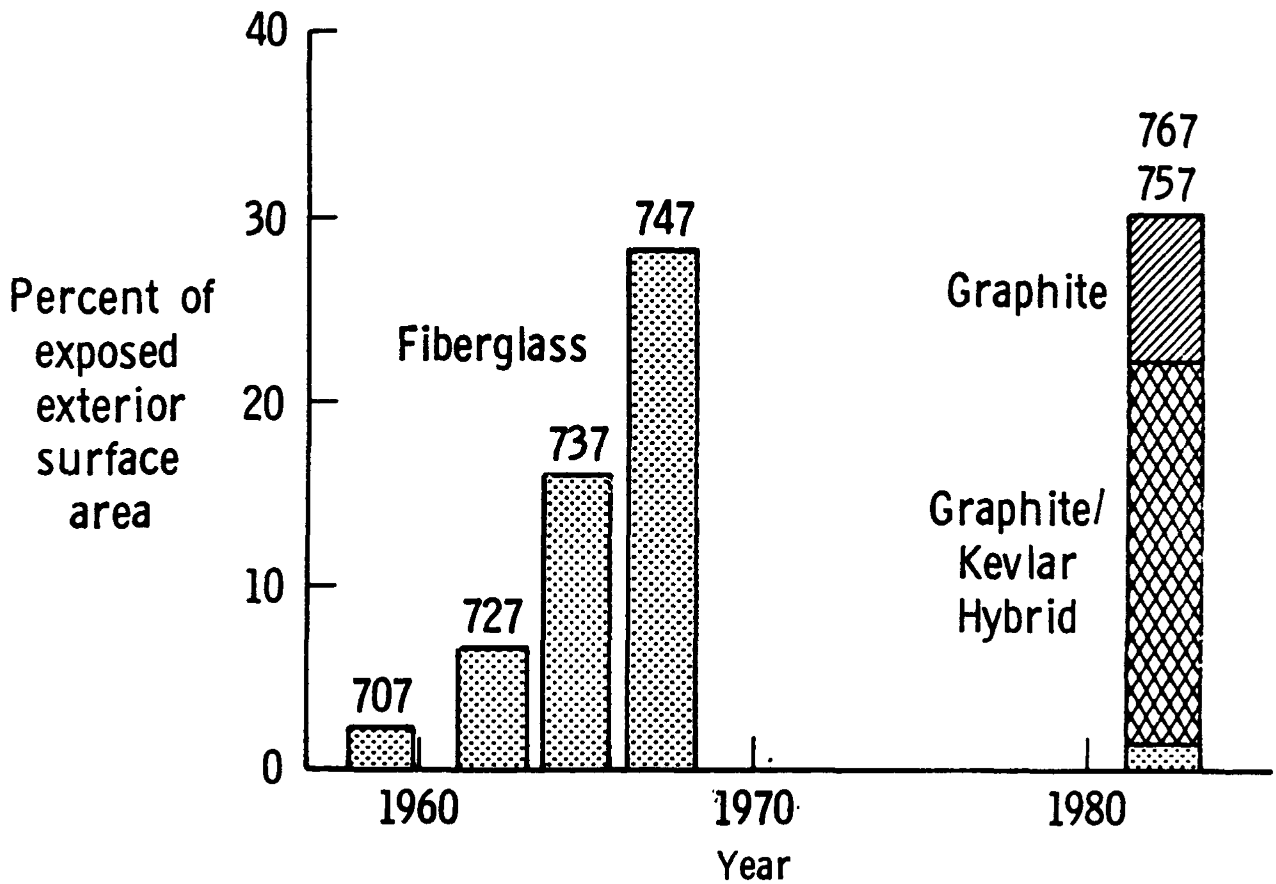

Figure 7

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OF POOR QUALITY

BOEING 767 COMPOSITE STRUCTURE APPLICATIONS

Although the Boeing 767 is primarily an aluminum airplane, the application of graphite and Kevlar composites represents a significant commitment. Weight saving was a significant factor, but expected improvement in maintainability was also an important consideration. A weight saving of over 2000 pounds was achieved through the use of graphite, Kevlar, and graphite/Kevlar hybrid composite materials. Most of the control surfaces, including rudders, elevators, spoilers, and ailerons, are being produced with graphite/epoxy composites. Graphite/Kevlar hybrids are used in numerous structures such as leading- and trailing-edge panels, cowl components, landing gear doors, and fairings (fig. 8). To maximize weight savings, thin gage composite facesheets were cocured onto Nomex honeycomb sandwich for a large number of the composite parts (ref. 9). In addition, significant interior applications of Kevlar/epoxy were included in ducting, stowage bins, partitions, lavatories, and escape system components. Weight savings of 25 to 30 percent were achieved where graphite and Kevlar composites were used rather than fiberglass/epoxy. It is expected that further performance improvements will be achieved in the next generation aircraft when primary wing and fuselage structures are fabricated with even more advanced composite materials.

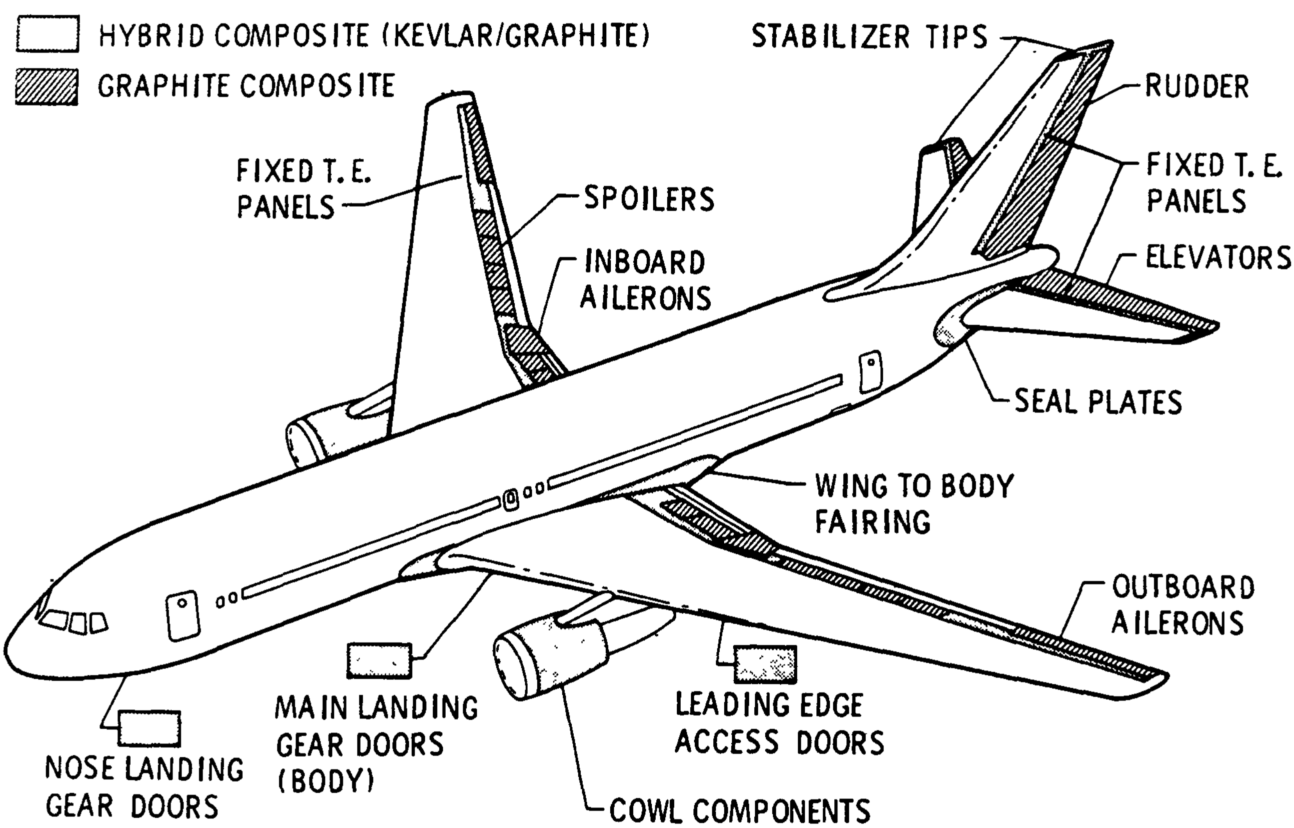


Figure 8

MATERIALS WEIGHT DISTRIBUTION FOR ADVANCED TECHNOLOGY AIRPLANE

The Boeing 767 aircraft incorporates state-of-the-art composite and metals technology in its baseline design. With increased emphasis on further material improvements and low-cost manufacturing methods, it is expected that the 1990 to 2000 transport aircraft will offer substantial performance and cost improvements compared to today's aircraft. One option would be that extensive advanced composites development during the 1980's could lead to an aircraft with up to 65 percent by weight of composite structure, with only about 11 percent advanced aluminum structure (fig. 9). This option would require that significant improvements be made in the damage tolerance characteristics of advanced composites and low-cost automated manufacturing concepts suitable for production must be developed. A second option could follow the path of extensive development of advanced aluminum alloys with somewhat lesser emphasis on advanced composites (ref. 10). Developments in aluminum/lithium alloys and powder metallurgy processes could lead to an aircraft with up to 54 percent advanced aluminum alloys and 25 percent advanced composites. In reality, the next generation aircraft will probably have a balance of materials somewhere between the two options indicated. The impetus for the extensive composites option will be on high performance and weight saving, whereas the emphasis for the advanced aluminum option will focus on modest performance and weight saving with less manufacturing facility changes required.

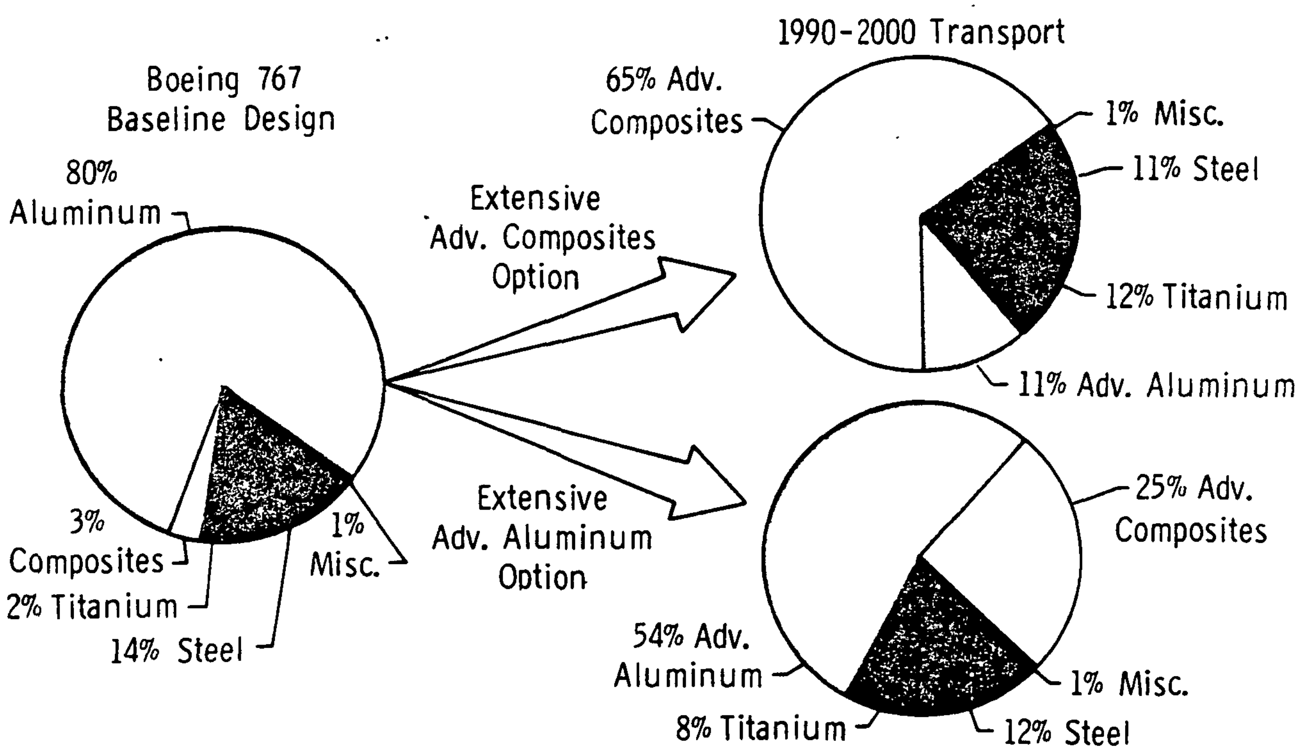


Figure 9

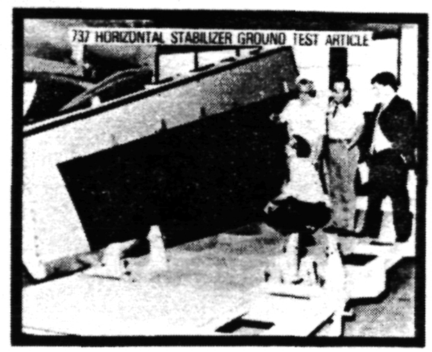
AIRCRAFT ENERGY EFFICIENCY (ACEE) COMPOSITE PRIMARY AIRCRAFT STRUCTURES

Since 1975, NASA has been sponsoring technology development programs with the aircraft industry to expedite the application of advanced composite materials to commercial transport aircraft. Secondary graphite/epoxy composite components, including rudders, ailerons, and elevators, have been designed, fabricated, tested, FAA-certified, and placed into commercial airline service. Studies are also under way to develop the technology for more complex medium primary composite components such as vertical and horizontal stabilizers (fig. 10). The empennage components present a significant challenge due to size, design requirements, load interaction, and manufacturing and tooling requirements (ref. 11). All three components--DC-10 vertical stabilizer, L-1011 vertical fin, and 737 horizontal stabilizer--have been successfully designed, fabricated, and tested to verify performance potential. An average weight saving of 24 percent was achieved for the three composite components shown in figure 10. The 737 graphite/epoxy horizontal stabilizers have been certified and installed on commercial aircraft for service. A DC-10 vertical stabilizer will enter service in the near future. These programs have made great strides in demonstrating composites technology and have provided an excellent opportunity to work FAA certification requirements for primary structures. However, scale-up problems and production cost issues must still be worked for wing and fuselage structures. NASA-sponsored studies are currently under way to resolve the remaining issues so that aircraft manufacturers can make production commitments to primary composite structures for the next generation aircraft.

TRANSPORT MEDIUM PRIMARY COMPONENTS

SIZE: 7' X 23'
WEIGHT: 780#
WEIGHT SAVED: 22.6%

SIZE: 9' X 25'
WEIGHT: 620#
WEIGHT SAVED: 28.4%



SIZE: 4' X 17'
WEIGHT: 204#
WEIGHT SAVED: 22.1%

Figure 10

U.S. ARMY/BELL ADVANCED COMPOSITE HELICOPTER AIRFRAME

The U.S. Army has an Advanced Composite Airframe Program (ACAP) under way to demonstrate advanced composite structures technology (ref. 12). Composite airframes have been built by Bell Helicopter (fig. 11) and Sikorsky Aircraft, and flight testing is currently under way. The Bell design makes use of graphite/epoxy, Kevlar/epoxy, fiberglass/epoxy, and fiberglass/polyimide to satisfy the design requirements. The Bell composite airframe was fabricated in two half-shells and bonded together along a longitudinal splice. The main cabin is fabricated with tape and broadgood composite prepreg materials using standard autoclave processes. The tail cone features a filament-wound truss structure for improved ballistic tolerance. The goals for the ACAP are 17 percent acquisition cost saving, 22 percent weight reduction, operational cost reduction, increased damage tolerance, low radar reflectivity, improved reliability and maintainability, and increased fatigue life. The two major structural requirements placed on the aircraft are ballistic tolerance and crashworthiness. In fact, these requirements are the primary design drivers for the airframe, and weight penalties were incurred to satisfy these criteria. The results of the ACAP program will provide valuable information to the military for future vehicles such as LHX and JVX aircraft.

Figure 11

ADVANCED COMPOSITE MATERIALS IN SPACE SHUTTLE ORBITER

The Space Shuttle orbiter has made extensive use of advanced composite materials to save structural weight and increase overall vehicle performance. Almost 11,000 pounds of advanced composite materials have been used to save over 3400 pounds of structural weight compared to baseline aluminum structure (fig. 12). The largest weight saving (900 pounds) was achieved in the graphite/epoxy payload bay doors. The second largest weight saving (over 700 pounds) was achieved in the boron/epoxy reinforced titanium truss members in the main engine thrust structure. Boron/aluminum is used in fuselage frame support struts and Kevlar/epoxy is used extensively in filament-wound pressure vessels. In addition, an extensive Kevlar/epoxy purge ducting system is used throughout the orbiter vehicle (ref. 13). If graphite/polyimide composites were used to replace existing aluminum structure, the allowable structural temperature could be increased from 350°F to 600°F. In addition to significant structural weight savings, a reduction in the thermal protection system would also result. It is estimated that a 30-percent reduction in the structural/thermal protection weight could be achieved. Also, if advanced carbon-carbon composites were used in the Shuttle nose cap and wing leading edges, even greater weight savings could be realized. Design studies (ref. 14) indicate that over 15,000 pounds of weight could be saved in the Space Shuttle orbiter through the use of advanced composites.

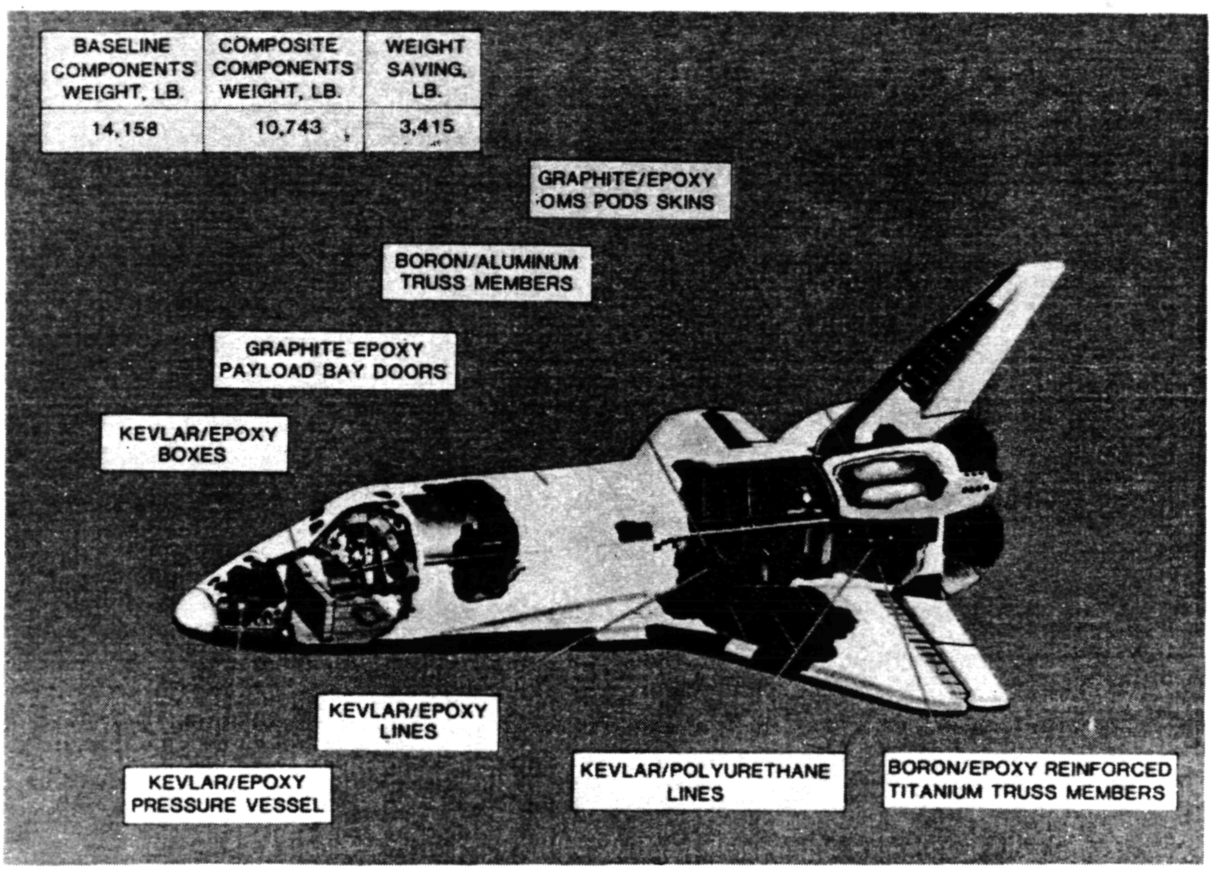


Figure 12

SPACE STATION CONFIGURATION

Although a specific configuration has not been established for Space Station, a reference configuration has been selected from the preliminary design studies conducted by NASA (fig. 13). This configuration consists of a set of linear trusses to which pressurized modules, subsystems, and user equipment are attached. The principal structural components are a keel and three booms at right angles to the keel. The keel is divided at the bottom to allow installation of the pressurized modules on the centerline of the keel (ref. 15). For the initial operational configuration, the weight of the truss structures is estimated to be 30,000 pounds out of 447,000 pounds, or 6 to 7 percent of the weight. Composites have been selected for the structural members of the truss structures because of the desire to have a lightweight structure with sufficient stiffness that no significant control problems will be encountered. Also, the low thermal expansion of composites (1×10^{-6} in/in/°F) compared to metals (aluminum: 12.5 to 13×10^{-6} in/in/°F) makes composites attractive to minimize thermal distortions of the truss structures as Space Station passes into and out of direct sunlight while orbiting the Earth.

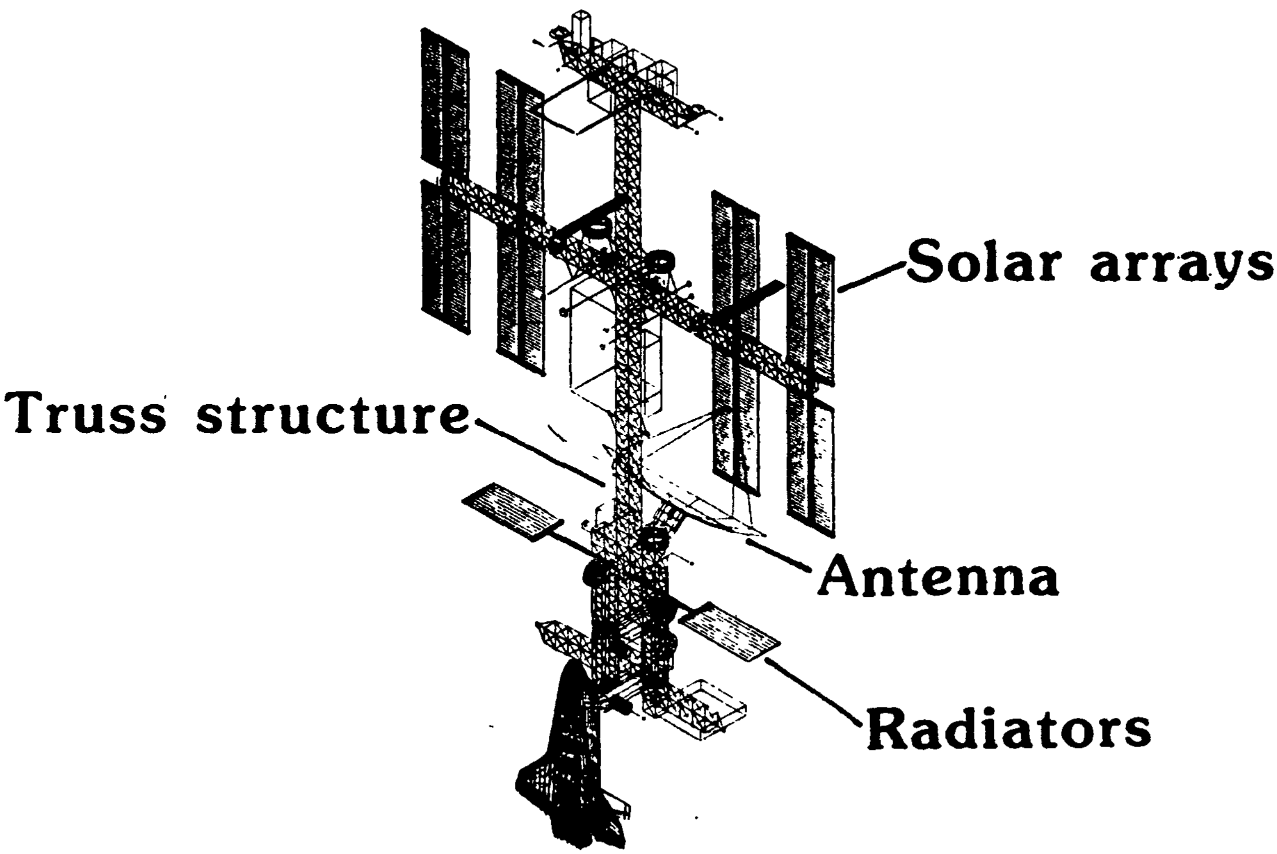


Figure 13

BARRIERS THAT LIMIT APPLICATION OF HIGH-PERFORMANCE COMPOSITES

The previous figures have illustrated the types of applications where composites are being used in the aerospace industry. However, the widespread use of composite structures that will be more highly loaded than those currently in use will require that materials be developed with improved damage tolerance and delamination resistance (fig. 14). Efforts under way to resolve these issues will be discussed in subsequent figures. The final portion of this paper will focus on manufacturing cost and some of the approaches being considered to lower the cost of composite structures.

- Damage tolerance
- Delamination resistance
- Manufacturing cost

Figure 14

EFFECT OF PROJECTILE IMPACT ON COMPRESSION STRENGTH

A limiting factor that has been identified for state-of-the-art graphite/epoxy composites is their sensitivity to impact damage. Impacts caused by dropped tools or foreign objects during takeoff and landing of aircraft can result in internal damage to laminated composite structures. The damage could include delamination between plies and through-the-thickness matrix cracks. An example of the effect of low-speed impact on the compressive stength of a 48-ply T300/5208 orthotropic laminate is shown in figure 15. The axial compressive strain applied to the laminate prior to impact is shown on the ordinate and the projectile impact energy is shown on the abscissa. The filled circles represent specimens that failed on impact and the open circles represent specimens that continued to support the applied load after impact occurred, even though they may have sustained local damage (ref. 16). The curve labeled "failure threshold" was faired between the open and filled circles and could represent an upper bound for the static compressive strain of graphite/epoxy laminates subjected to low-speed impact damage. Impact energies of 100 in-lb and higher reduced the strain capability of the laminate from 0.009 (undamaged) to 0.003. Even nonvisible impact damage can reduce the failure strain capability from 0.009 to 0.005. Designs of secondary and empennage structures have been governed primarily by stiffness requirements with design ultimate strains of about 0.003. Current resin/fiber systems can meet this requirement without a weight penalty. However, for large primary wing and fuselage structures, which are designed by strength requirements, higher strain capability is required if maximum utilization of composites is to be achieved. Numerous research programs are currently under way to develop resin/fiber systems to meet the higher strength requirements.

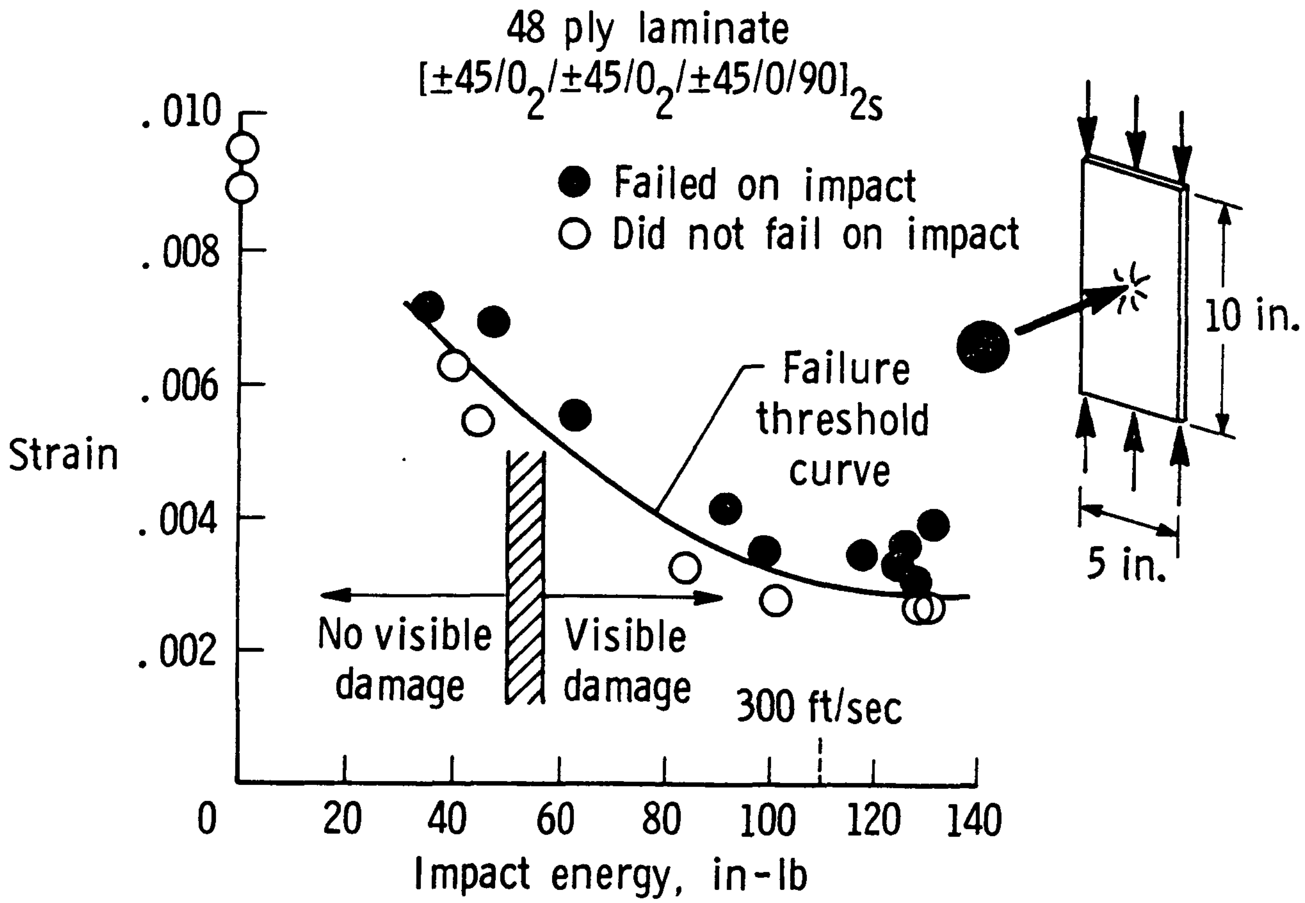


Figure 15

EFFECT OF DELAMINATION SEVERITY ON COMPRESSION FAILURE OF GRAPHITE/EPOXY LAMINATES

One of the most commonly observed failure modes in composites is separation of individual plies by delamination. Delamination may result from low-velocity impacts, from eccentricities in structural load paths that induce out-of-plane loads, or from discontinuities in the structure which create local out-of-plane loads (ref. 17). A primary concern is the effect such delaminations may have on the strength of composite materials. Figure 16 shows the effect of delamination severity on compression failure of typical graphite/epoxy laminates. Simulated delaminations, produced by teflon film disks, can cause a significant reduction in the compressive strain capability of the laminate. A single implanted delamination near the surface of the laminate can result in a 25-percent decrease in the strain capability, whereas multiple delaminations located near both surfaces and at the laminate mid-plane can cause up to a 50-percent decrease in compression strain to failure. As illustrated in figure 15, low-velocity impact can cause severe strength reduction. Impact damage that may be only barely visible on the surface of the laminate can cause extensive internal delamination and reduced strain capability. A laminate subjected to a severe impact that causes visible surface damage can result in a 60- to 70-percent reduction in the compressive failure strain capability of the laminate. Research is currently under way to develop analytical methods to predict delamination onset and growth and methods to improve the delamination resistance of laminated composite materials. Resin/fiber systems with improved interlaminar fracture toughness and material forms with through-the-thickness reinforcement offer potential for improved delamination resistance.

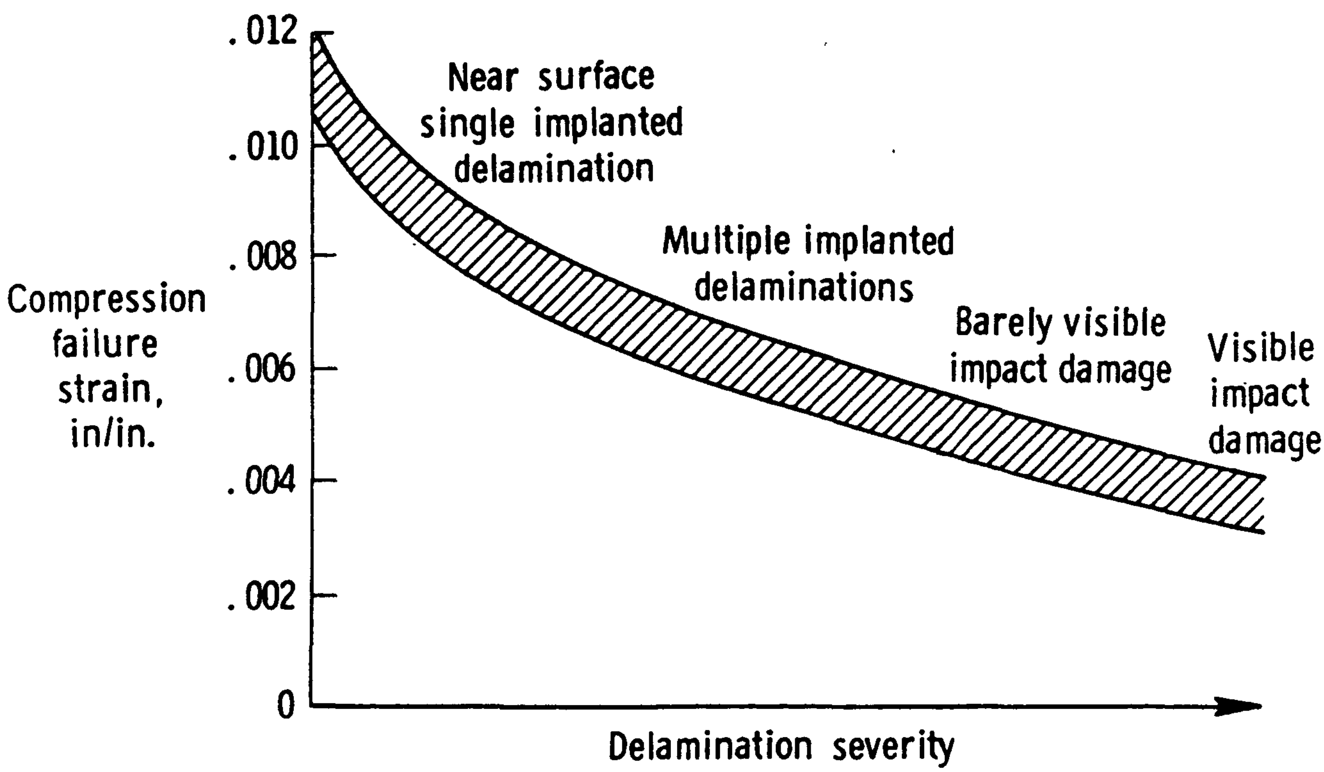


Figure 16

CYCLIC COMPRESSION FATIGUE LIFE TRENDS FOR T300/5208 GRAPHITE/EPOXY LAMINATES

Previous discussions for figures 15 and 16 focused on static strength reduction as a function of delamination and impact damage. An additional concern is delamination growth caused by cyclic fatigue loading. Figure 17 shows data on cycles to failure as a function of maximum cyclic compression strain for a 38-ply T300/5208 graphite/epoxy laminate representative of an upper surface transport wing skin (ref. 17). Three different types of defects are considered: (1) single circular inserts of different diameters located at different interfaces to simulate delamination, (2) a laminate containing a 0.5-inch-diameter hole, and (3) laminates that have been subjected to various levels of low-velocity impacts. The impacted laminates suffered the most severe degradation in the compressive strain at failure and the laminates with single implanted delaminations suffered the least degradation in failure strain. Although the static residual strength of laminates with implanted delaminations is higher than the strength of laminates with holes, the rate of strength degradation is also higher, as indicated by the steeper slope for the bounding curves shown in figure 17. As the cycles to failure approach 10^6 to 10^7 cycles, all three damage types result in similar cyclic strain degradation for the laminates. These results not only emphasize the importance of preventing delamination in graphite/epoxy composites, they also indicate the need to develop methods to suppress delamination growth. Research is currently under way to develop arrestment techniques analogous to buffer strips used to arrest cracks in tension-loaded panels.

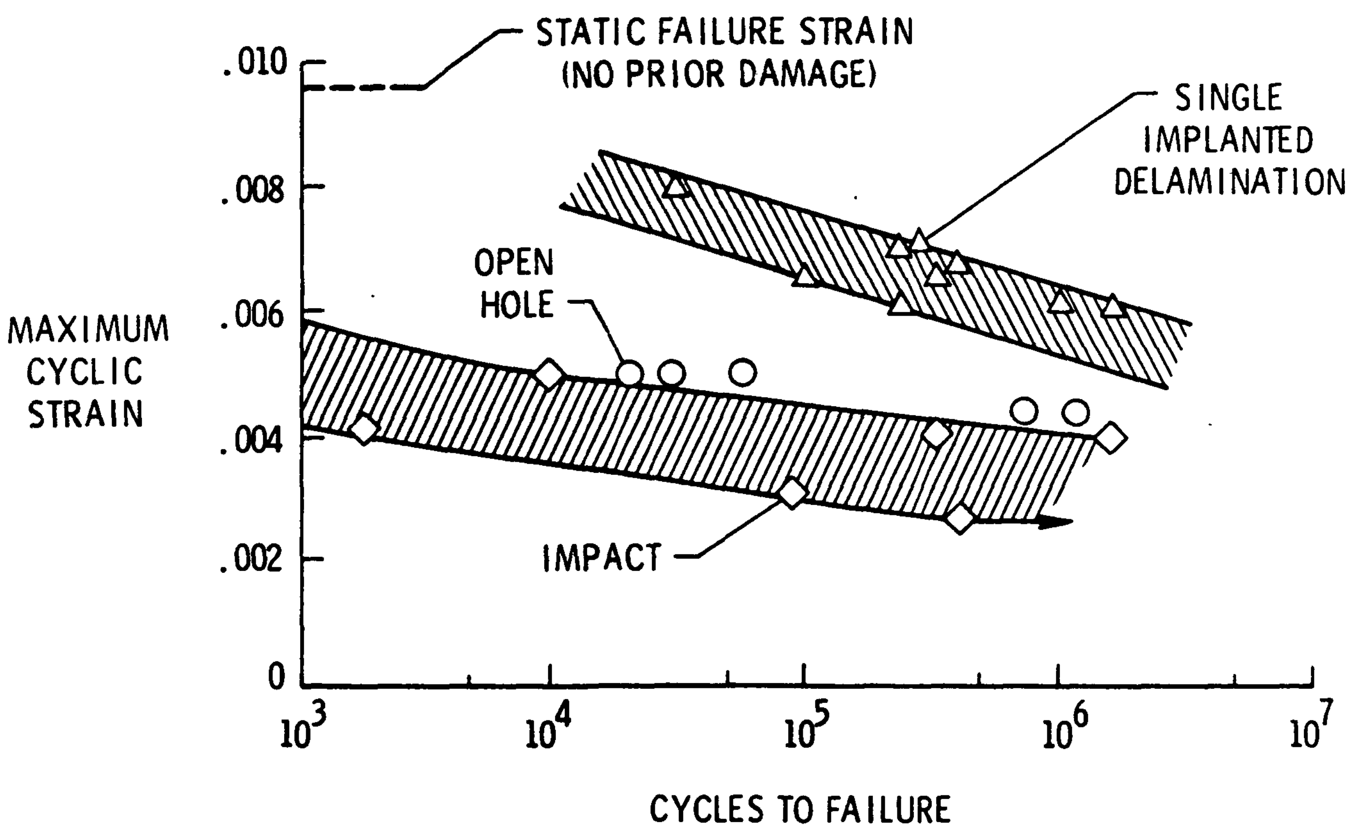


Figure 17

IMPACT FAILURE THRESHOLD STRAIN

Fabric Versus Tape

Research is currently under way to develop concepts for improving the damage tolerance of compression-loaded composite structures (ref. 18). The test results for two concepts, woven fabrics and through-the-thickness stitching, are shown in figure 18. The failure-threshold curve for the fabric specimens is 25- to 30-percent higher than for the all-tape laminates. Interlaminar fracture toughness tests conducted on tape and woven fabric composites also indicated significant improvements in the fracture toughness of the fabric laminates compared to the tape laminates. The cross-plies of woven fabric are mechanically linked together, thereby reducing the number of delamination interfaces. Also, the through-the-thickness reinforcement provided by the fiber crimp may provide some improvements in interlaminar and transverse strengths. The second concept investigated was stitching the graphite/epoxy laminate through the thickness with Kevlar yarns. The results shown in figure 18 indicate a large increase in the failure threshold compared to the tape and fabric laminates. The transverse reinforcement was adequate to suppress delamination and served to mechanically lock the laminate together at discrete points. The failure mode changed from a delamination mode to a higher-energy transverse-shear mode. Additional research is required to establish the most efficient material forms to suppress delamination. Concepts such as 3-D weaving, braiding, and stitching are currently being studied.

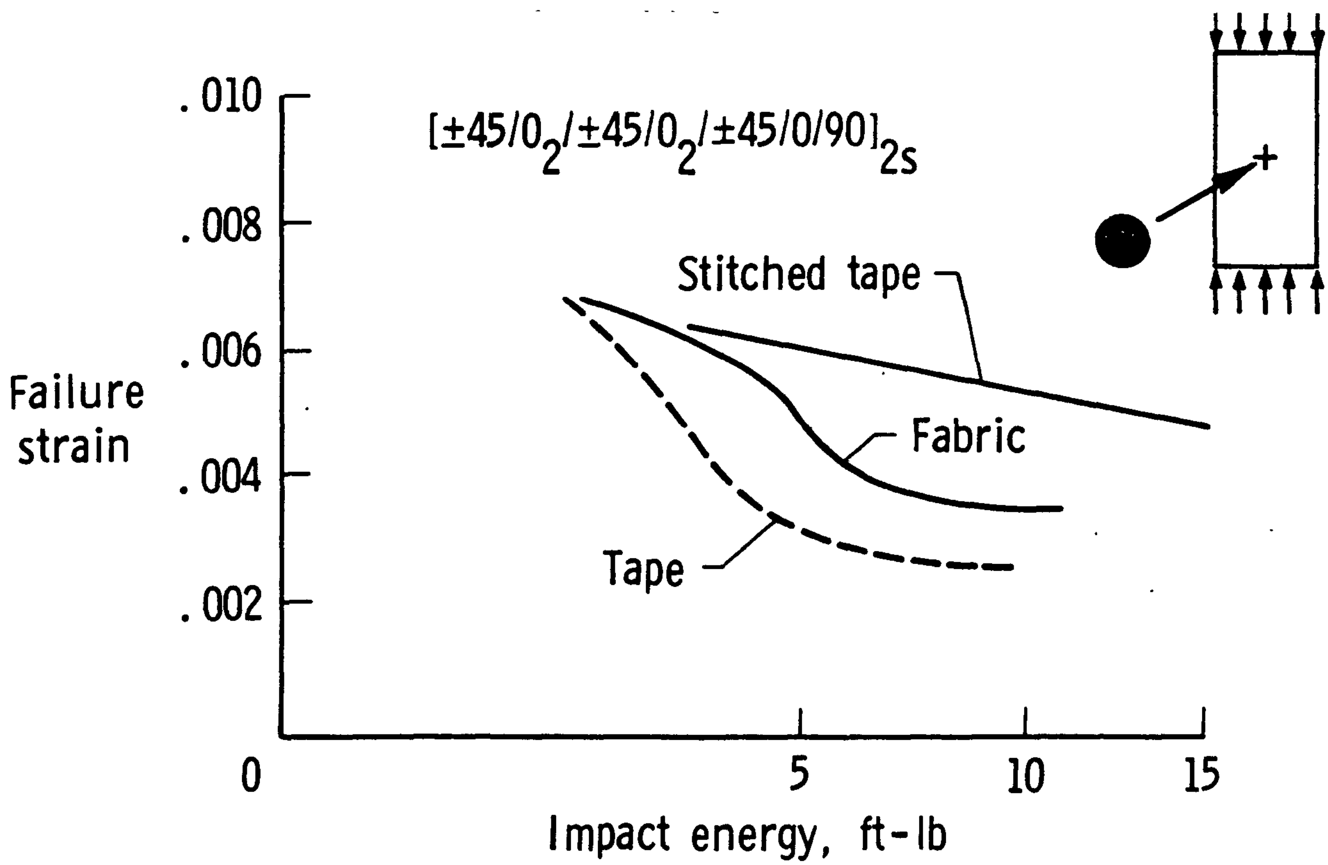


Figure 18

INTERLAMINAR FRACTURE TOUGHNESS OF COMMERCIAL GRAPHITE COMPOSITES

To translate the weight savings potential of resin-matrix composites into significant increases in operating efficiency, their resistance to impact damage and delamination needs to be improved. Such improvements would enable the use of higher design strains and avoid "knock-down" factors to account for reduced structural properties resulting from damage or unexpected loads. To meet the need for improved damage tolerance, a significant research effort is under way to develop resin matrices with improved toughness. Interlaminar fracture toughness can be evaluated through tension edge-delamination tests and double-cantilever-beam tests. Figure 19 shows a bar chart (ref. 19) of interlaminar fracture toughness (G_{Ic}) values for several commercially available composites. Only the resin designation is shown because the interlaminar fracture toughness is controlled by the properties of the resin. The first-generation thermosets are the most commonly used 350°F cure epoxies and are characterized by low fracture toughness. Second-generation thermosets have approximately twice the fracture toughness values exhibited by the first-generation epoxies. Although this improvement is significant, the increase in G_{Ic} is still substantially lower than the near-term target range of 4 to 6 in-lb/in^2. Thermoplastic materials offer the potential for much higher toughness but suffer from the disadvantages of high processing temperatures and sensitivity to solvents. The development of semicrystalline polymers, such as PEEK, manufactured by Imperial Chemical Industries, offer hope for achieving high toughness, good hot/wet compressive strength, and solvent resistance. The large gap between the 350°F thermosets and thermoplastics needs to be filled in the near term by a "third generation" of thermosets until adequate research and development on thermoplastics can be conducted to establish the potential of these materials.

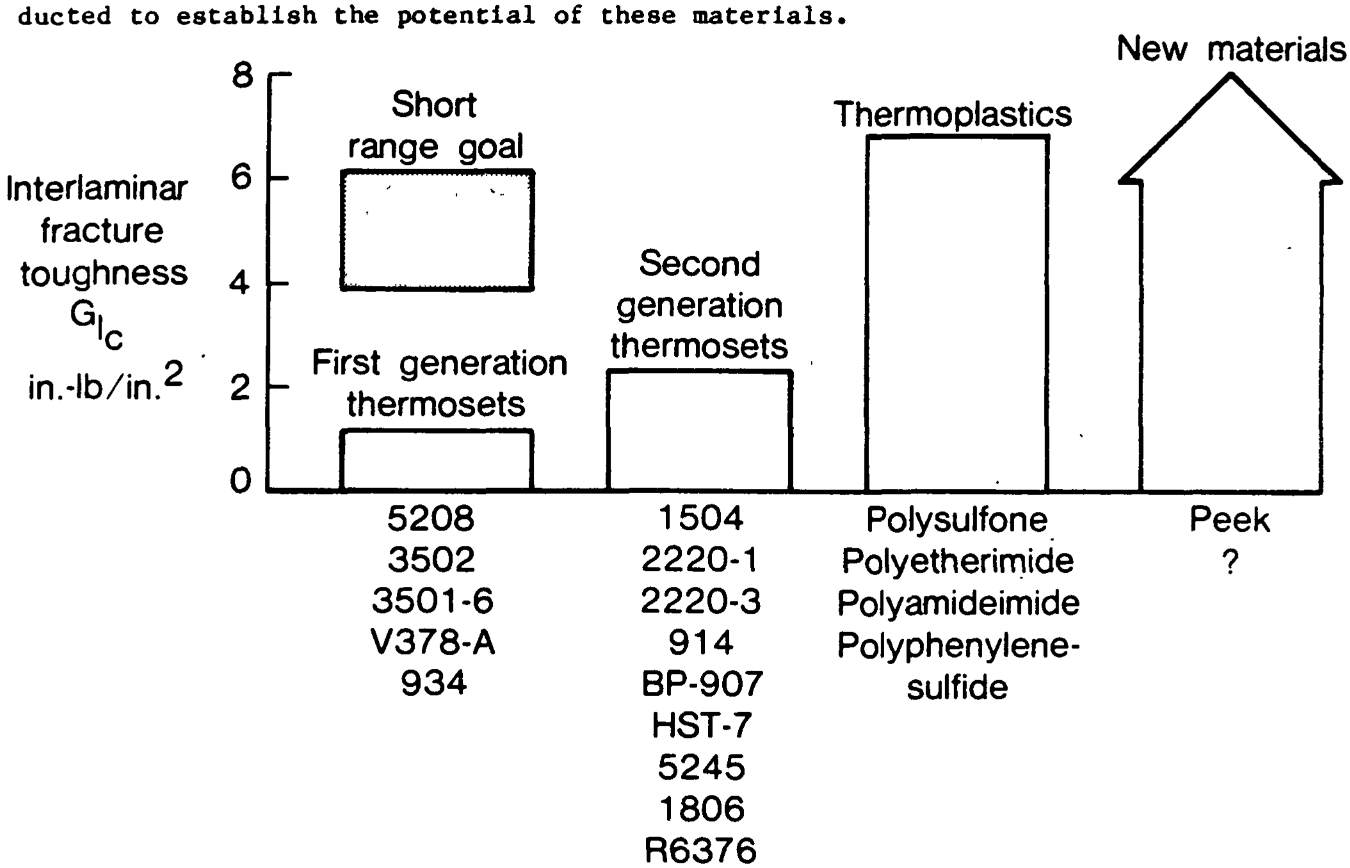


Figure 19

DEVELOPMENT OF ADVANCED POLYMER MATRIX MATERIALS

Research programs are currently under way to develop resin matrices with improved toughness to meet the need for composites with improved damage tolerance. However, in the development of these materials, the polymer chemist is also faced with the challenge of maintaining high hot/wet compressive strength. A schematic diagram showing the hot/wet compressive strength and matrix toughness of current matrix materials and the goal (ref. 19) for development of new materials is shown in figure 20. The 350°F cure epoxies, such as Narmco 5208, manufactured by Narmco Materials, a subsidiary of Celanese Corporation, have good hot/wet compressive strength but suffer from low toughness. General approaches taken to increase toughness by adding elastomers or changing the curing agents to alter polymer chain chemistry all have resulted in lowering the hot/wet compressive strength. This reduction is undesirable because composites are generally used in compression-critical structures and may be subjected to service use temperature approaching 180°F in a high relative humidity environment.

The major approaches currently being considered to achieve a combination of high toughness and high hot/wet compressive strength include investigation of semi-crystalline thermoplastics, polymers with strong hydrogen bonding, highly aromatic amorphous thermoplastics, and lightly crosslinked thermoplastics. Extensive research and development, however, will be required to achieve the desired property goals.

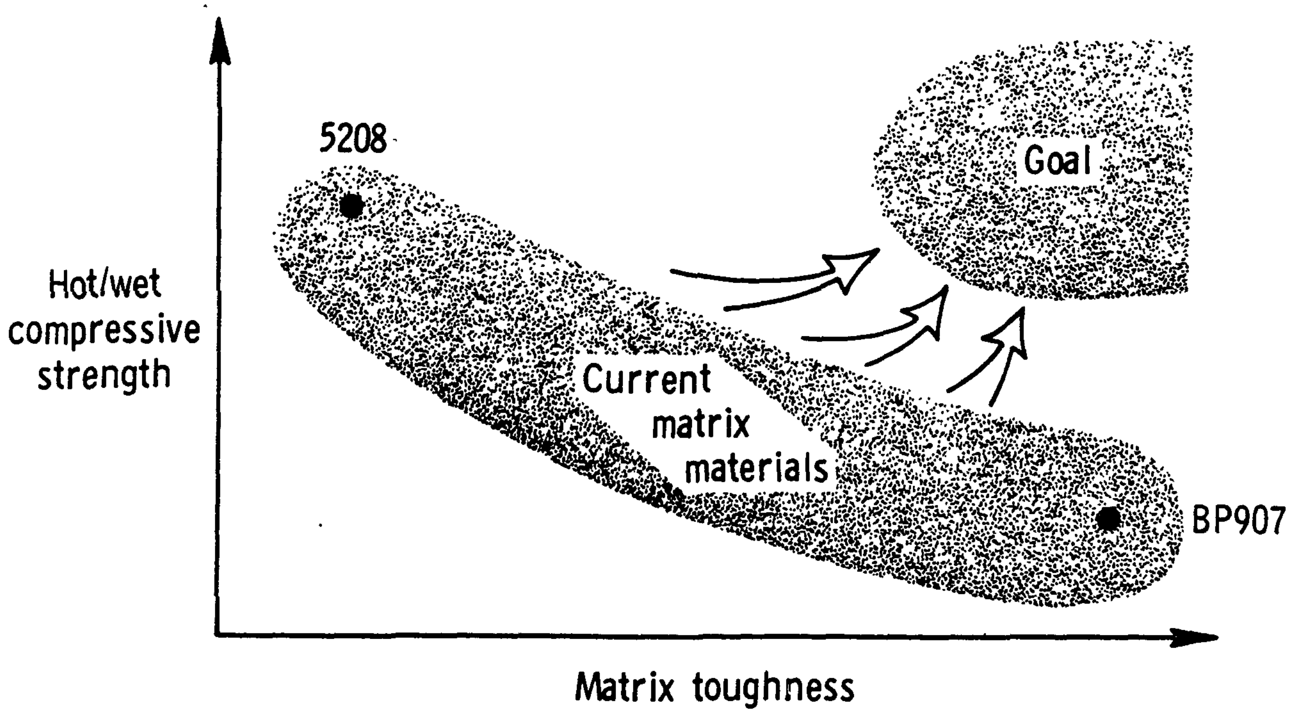


Figure 20

CHARACTERISTICS OF GRAPHITE-REINFORCED THERMOSET AND THERMOPLASTIC COMPOSITES

As discussed previously, studies are under way to develop matrix materials with improved fracture toughness and good hot/wet compressive strength. Recent results indicate that some thermoplastic materials may meet those requirements. The data* shown in figure 21 indicate some of the characteristics of a state-of-the-art epoxy (Narmco 5208) and a new thermoplastic (APC 2 PEEK) developed by Imperial Chemical Industries (ICI). The 5208 epoxy must be refrigerated to extend its shelf life, whereas the PEEK material has an unlimited shelf life when stored at room temperature. The processing characteristics of the two materials are quite different. The 5208 epoxy system can be cured at 350°F for 3 hours under a pressure of 85 to 100 psi. Additional post cure can be done if higher structural operating temperature of the material is desired. The PEEK material must be consolidated at 720°F for one-half hour at a pressure of 200 psi. The glass transition temperature for the PEEK material is somewhat lower than for the 5208 epoxy. A major difference between the two materials is in the interlaminar fracture toughness and impact resistance. The PEEK material has an interlaminar fracture toughness, G_{Ic}, of 12.0 in-lb/in^2 compared to 0.5 in-lb/in^2 for the 5208 epoxy. The compression-after-impact failure strain for the PEEK material is a factor of 2.7 higher than for the 5208 epoxy. Research is currently under way to arrive at high-performance materials that meet structural requirements and at the same time offer low-cost processing characteristics.

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*The data shown were obtained from product data sheets published by Narmco Materials and Imperial Chemical Industries, respectively.

	5208 Epoxy	APC 2 Peek
Storage requirement	0°F	Room temperature
Shelf life	6 months$^{(+)}$	Unlimited
*Processing time/temp/pressure	3 hr/350°F/85-100 psi	0.5 hr/720°F/200 psi
Glass transition temp.	380°F	290°F
Interlaminar fracture toughness, G_{Ic}, $\frac{\text{in-lb}}{\text{in}^2}$	0.5	12.0
Compression-after-impact failure strain, in/in. (1000 $\frac{\text{in-lb}}{\text{in.}}$ impact)	0.003	0.008

*Dependent upon thickness

Figure 21

MAJOR CHALLENGES FOR CONTINUED GROWTH OF ADVANCED COMPOSITES

The materials development efforts discussed in the previous figures are expected to produce a family of tough new resins. Development of materials with improved damage tolerance and impact resistance will expand the market for composites because of the improved structural efficiency which can be achieved by utilizing composites to higher strain levels. However, continued growth of the advanced composites market will depend not only on having improved materials but also on reducing the cost to fabricate structures from composites. Two approaches to meeting this challenge are listed in figure 22. Development of low-cost, innovative material forms such as two-dimensional (2-D) and three-dimensional (3-D) woven fabrics and braided structures offer significant potential for further improvement of damage tolerance and impact resistance with a 15- to 20-percent reduction in cost. If structural reinforcement elements can be woven or braided into net shape fiber preforms in one operation, thus resulting in fewer parts and less labor, the cost of the finished structure could be less than that of a conventionally produced panel.

Another approach to reduce the cost of composite structures is to develop manufacturing processes which are less labor intensive than the hand-layup tape method currently employed in most composite fabrication programs. Low-cost manufacturing and design concepts currently being evaluated include automated material placement, filament winding, pultrusion, and thermoforming.

- Development of low-cost innovative material forms
  - 2D and 3D woven fabrics
  - Braided structural elements
- Development of low-cost manufacturing and design concepts
  - Automated material placement
  - Filament winding
  - Pultrusion
  - Thermoforming

Figure 22

AUTOMATED COMPOSITE FABRICATION PROCESSES

As indicated in figure 22, one of the major challenges for continued growth of advanced composite materials is the development of low-cost manufacturing concepts. Figure 23 shows four different processes that have potential to meet that challenge. Weaving and braiding have the potential to produce continuous net-shape 2-D and 3-D fiber preforms. These preforms could be subsequently infiltrated with resin or possibly be produced with a low tack preimpregnated fiber tow. Automated material placement can be accomplished using computer-controlled tape-laying machines. The part size is limited to the work area of the machine. Tape-laying machines are more suited to flat or moderately curved parts. Accurate tape spacing and orientation can be accomplished through a computer-controlled robot-like tape-dispensing head. Pultrusion is a process that offers possibilities for producing continuous composite shapes such as stiffeners, panels, tubes, etc. Wet resin or impregnated tape materials may be used. Shapes are controlled by the die configuration. Filament winding has been used extensively to produce tension-critical pressure vessels. Recent resin developments and innovative tooling and pressurization techniques make filament winding an exciting concept to produce large structure. Entire aircraft fuselage segments have been wound and it is now possible to filament wind more complex shapes such as aircraft wing structure and control surfaces. Tremendous cost savings (50 percent and more) are anticipated through the use of filament-winding technology.

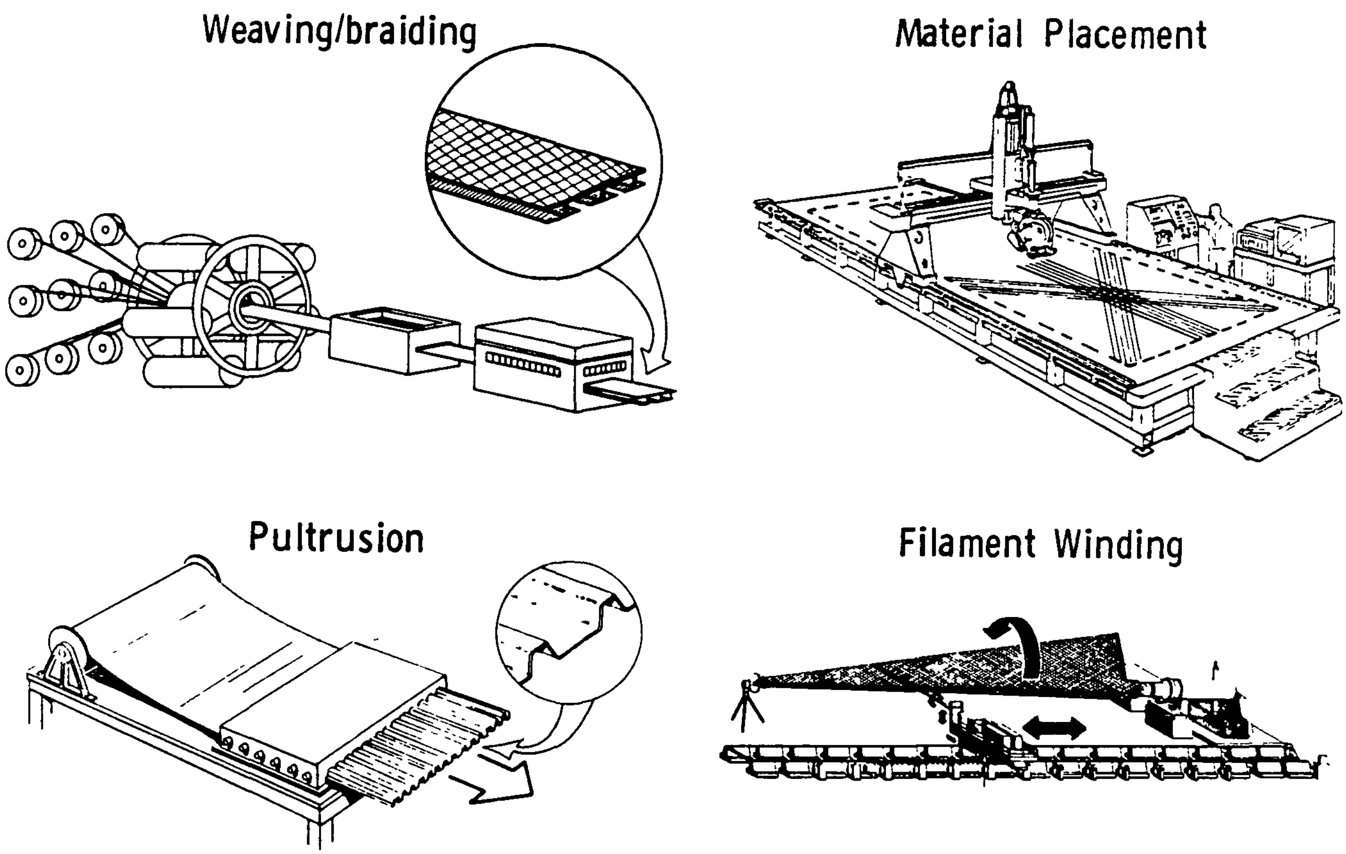

Figure 23

COST COMPARISON OF FABRICATION METHODS FOR GRAPHITE/EPOXY COMPOSITES

The relative cost to fabricate graphite/epoxy composites is shown in figure 24 for hand layup, preplied broadgoods, tape-laying machine, and filament winding. The relative cost includes material cost and labor cost for moderately complex structural shapes. Approximately 1.5 pounds/hour of graphite/epoxy preimpregnated tape can be laid-up by hand. Three to four plies of preplied broadgoods can be laid-up at a rate of 3 pounds/hour. However, the materials are more costly because of the material supplier labor charges for preplying. The finished structure costs about 15 percent less than the structure produced with the hand-layup process. The automated tape-laying machine can lay approximately 10 pounds/hour of unidirectional preimpregnated tape at a total cost of about 60 percent of the hand laid-up material. The filament-winding process is highly automated and approximately 400 pounds/hour of graphite/epoxy material can be wound. In addition, wet winding eliminates the preimpregnation process; hence, the filament-winding material costs about 50 percent less than preimpregnated tape. The finished filament-wound structure costs only about 26 percent as much as the more labor-intensive hand laid-up structure. The filament-winding process is currently being seriously considered as a low-cost fabrication method. Performance improvements in filament-winding resins and compaction procedures that produce low void content structures are two reasons for recent interest in the filament-winding fabrication method.

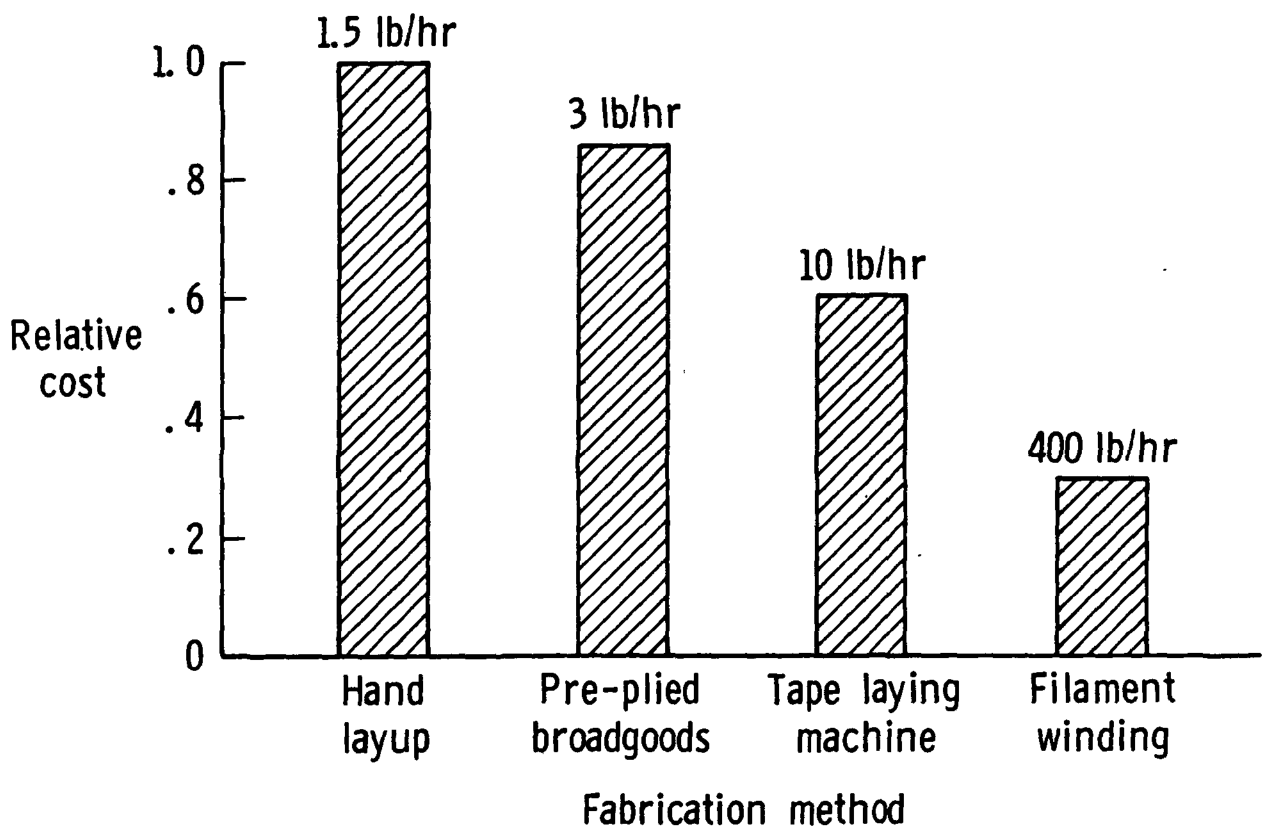

Figure 24

INNOVATIVE FABRICATION CONCEPTS

Innovative fabrication concepts must be developed if composite structures are to be cost effective in the next generation of aircraft. Figure 25 depicts two structural configurations that would be fabricated by vastly different fabrication concepts. The built-up structure is representative of today's aluminum aircraft wherein a large number of parts are mechanically fastened together to form the finished structure. The built-up structure is highly labor intensive and detailed analytical procedures are required to account for a variety of details such as stress concentrations, skin/stiffener attachment, and stiffener buckling modes. The integrated structural configuration utilizes an automated filament-winding fabrication process to achieve a low-cost finished structure. Integral stiffening can be incorporated into the design and fabrication process. Although the winding angles may be tailored for specific strength and stiffness, it is expected that the design and analysis methods will be somewhat simplified. Some of the composite structure designs of the past have been constrained to be retrofittable to aluminum aircraft; hence, the composite components looked similar to their metal counterparts. In the future, composites will be used more extensively as baseline structure and more design freedom will be available to the structural designer. For composites to be cost effective, simpler designs and automated fabrication concepts must be developed.

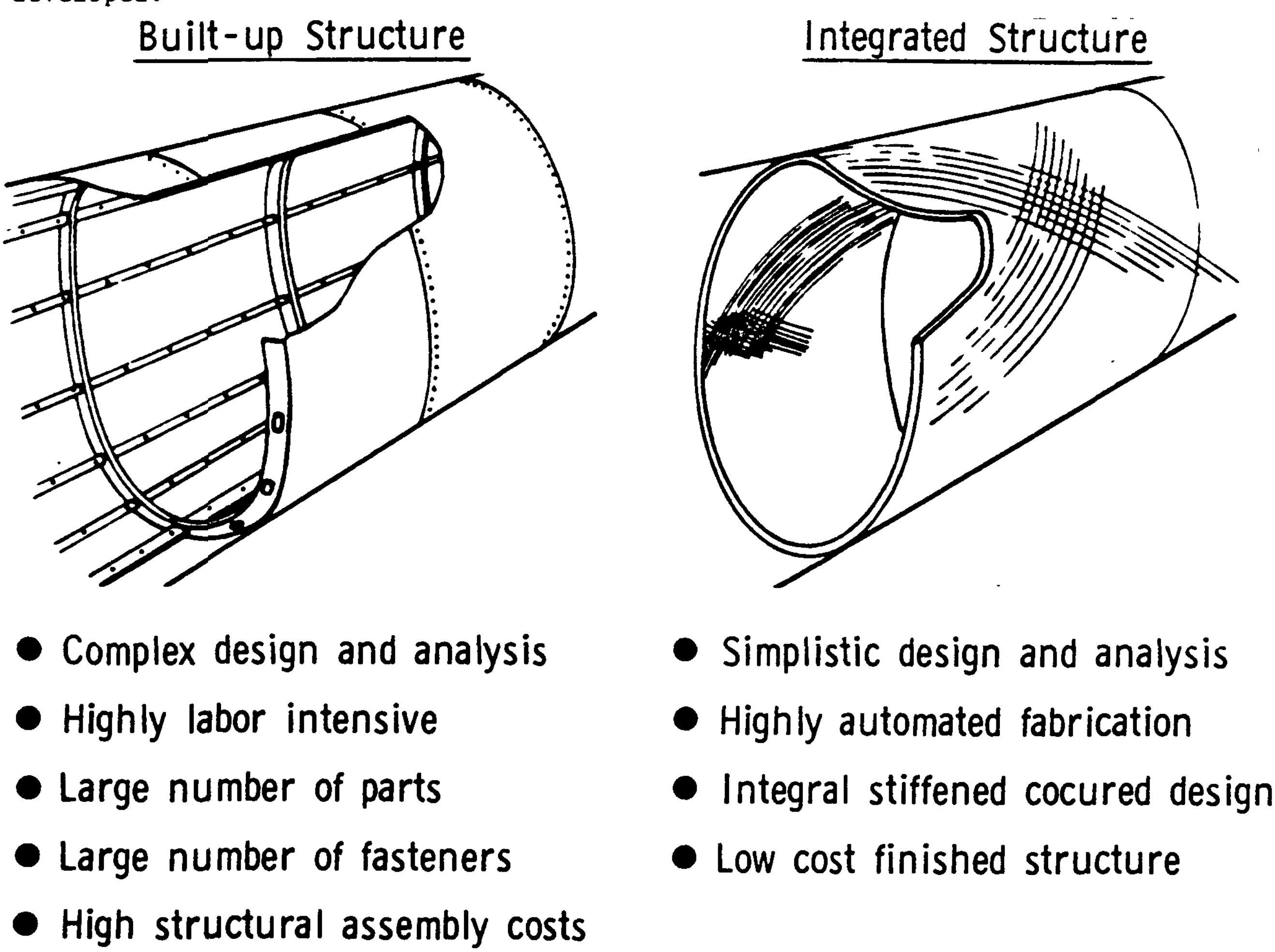

Figure 25

FILAMENT-WOUND GRAPHITE/EPOXY FUSELAGE FOR BEECH STARSHIP

The graphite/epoxy fuselage shown in figure 26 was filament wound by Fiber Tek, Inc., for the new Beech Starship. The fuselage is constructed with inner and outer 3-ply graphite/epoxy skins that are cocured onto a Nomex honeycomb sandwich. Local reinforcements for windows, doors, windshield, and frames are added during the filament-winding process and are all cocured with the skins and honeycomb sandwich. Hard-point attachments for the wing carry-through structure are also included in the winding process. Beech Aircraft is also evaluating other fabrication concepts, including conventional autoclave processing of tape and broadgood materials, for comparison with the filament-wound structure. Production cost estimates will be compared for the various fabrication concepts. In addition, mechanical properties and structural integrity will be compared for the various fabrication concepts.

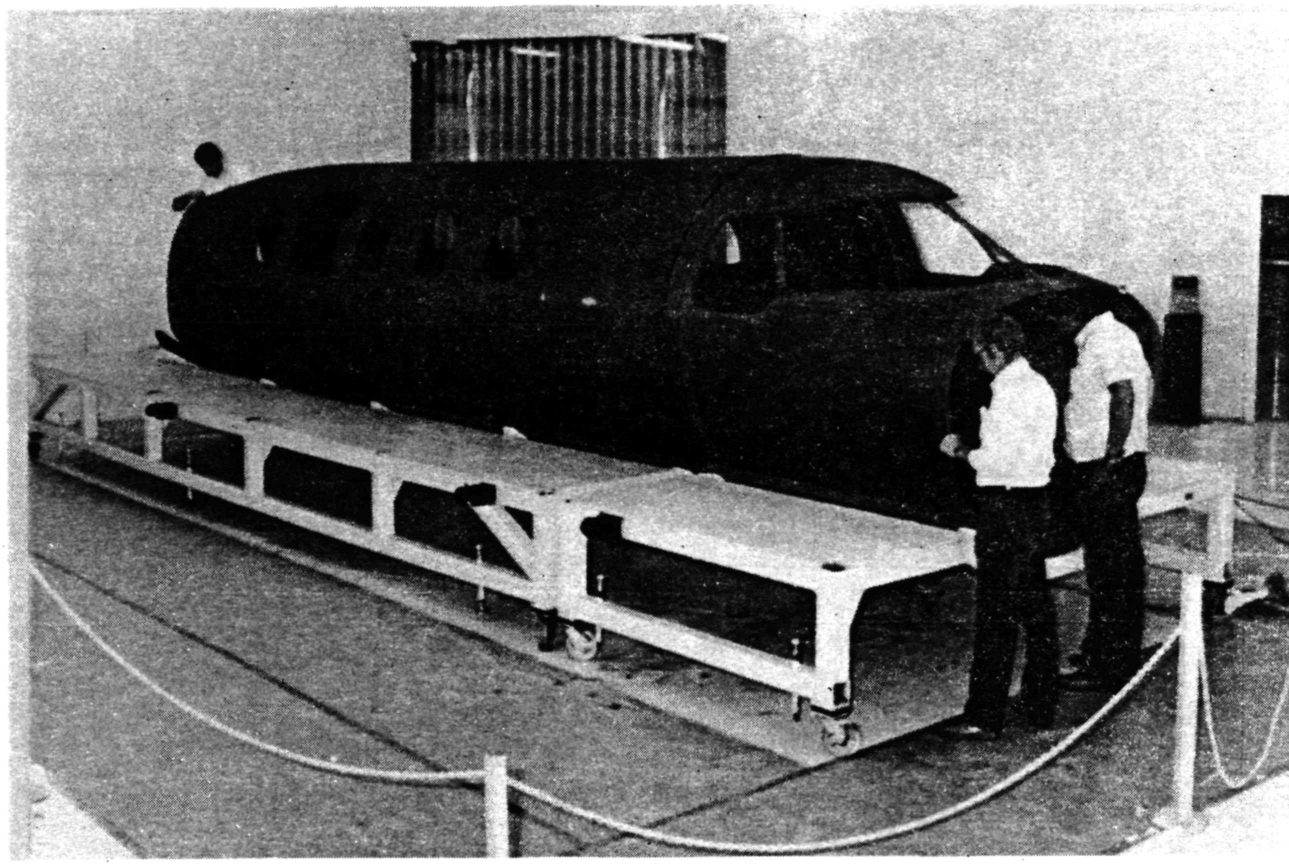

Figure 26

FACTORY OF THE FUTURE

Composites technology is in a rapid state of development which is expected to continue well into the next decade. As discussed earlier in this paper, research is focused on both development of new materials and new fabrication processes. Today the bulk of aerospace composite structures are fabricated using prepreg tape, hand layup, and autoclave curing at 350°F at pressures up to 200 psi. However, the trend to use more thermoplastic materials calls for higher processing temperatures, 700°F to 800°F, and different processing techniques such as pultrusion or thermoforming. Also, the equipment and procedures for filament-winding structures are very different from that used for autoclave curing of thermoset laminated structures. Because of these and other factors, planning the "factory of the future" is a difficult and challenging task. The decisions on types of equipment and plant layout will be strongly influenced by what happens in the material development efforts under way and how successful new manufacturing approaches are in lowering the cost.

Although much uncertainty exists in the design of new facilities to produce composite hardware, certain general observations can be made about the factory of the future. These are listed in figure 27. Because current processes are labor intensive, future composite processing is expected to be highly automated to reduce cost. This will likely include automated composite fabrication; computer feedback controlled processing; robotic cutting, drilling, and trimming; and automated real-time NDE. In addition to reducing cost, automation should also result in less property variability and improved quality control.

- Automated composite fabrication
    - Tape and ply laminating
    - Pultrusion
    - Thermoforming
    - Filament winding
- Computer feedback controlled processing
    - Analytical model of cure
    - In-situ sensors
    - Controlled temperature, pressure, and viscosity
- Robotic cutting, drilling, and trimming
    - Laser
    - Water jet
- Automated real-time NDE
    - Ultrasonics imaging
    - X-ray
    - Acoustic emission
    - In-situ sensors

Figure 27

SUMMARY

Major advancements have been made in the development of advanced composite materials during the past decade. Composites have moved from the research laboratory to the production floor, where they are baseline for many aerospace hardware components. Design data bases and in-service durability have been established for a variety of service environments. Many of the applications of composites have been for replacement of metal parts on existing designs with an average weight savings of approximately 20 to 25 percent. However, the full weight reduction potential of composites can only be realized when the damage tolerance of composites is increased such that they can be utilized at strain levels significantly higher than the 0.004 limit currently used in many aerospace applications.

A significant level of research is currently focused on the development of tough resins and high strain fibers in an effort to gain improved damage tolerance. Moderate success has been achieved with the development of new resins such as PEEK and additional improvements look promising with new thermoplastic resins. Development of innovative material forms such as 2-D and 3-D woven fabrics and braided structural subelements is also expected to improve damage tolerance and durability of composite hardware.

The new thrust in composites is to develop low-cost manufacturing and design concepts to lower the cost of composite hardware. Processes being examined include automated material placement, filament winding, pultrusion, and thermoforming. The factory of the future will likely incorporate extensive automation in all aspects of manufacturing composite components. The key points made in this paper are listed in figure 28.

- Fivefold reduction in graphite fiber cost achieved during past decade
- Extensive application of composites projected for next generation military and commercial aircraft
- Higher performance fiber and resin systems are required for improved damage tolerance of composites
- Low-cost innovative material forms and manufacturing processes are required for continued growth of composites

Figure 28

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